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DREDGED MATERIAL RESEARCH PROGRAM

TECHNICAL REPORT D-77-21

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SIZING OF CONTAINMENT AREAS FOR DREDGED MATERIAL

by

Suzanne E. Lacasse, T. William Lambe, W. Allen Marr

Constructed Facilities Division
Department of Civil Engineering
Massachusetts Institute of Technology
Cambridge, Mass. 02139

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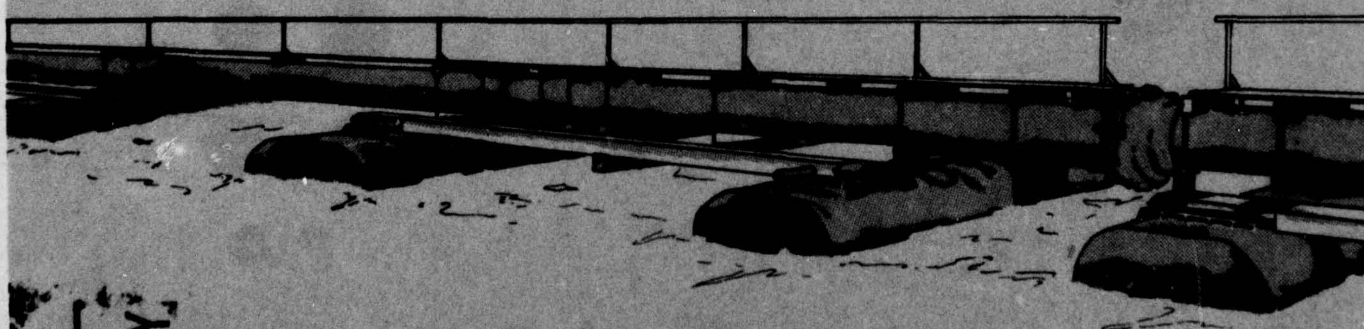

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SUBJECT: Transmittal of Technical Report D-77-21

TO: All Report Recipients

1. The report transmitted herein (Incl 1) represents the results of one of the research efforts accomplished as part of Task 2C (Containment Area Operations Research) of the Corps of Engineers' Dredged Material Research Program (DMRP). Task 2C is part of the DMRP Disposal Operations Project, which, among other considerations, includes research into the various ways of improving the efficiency and acceptability of facilities for confining dredged material on land.

2. Confining dredged material on land is a relatively recent disposal alternative to which practically no specific design or construction improvement investigations (much less applied research) have been addressed. Being a form of a waste-product disposal, dredged material placement on land has seldom been evaluated on other than purely economic grounds with emphasis nearly always on lowest possible cost. In the last several years, there has been a dramatic increase in the amount of land disposal necessitated by confining dredged material. Attention necessarily is directed more and more to the environmental consequences of this disposal alternative and methods for minimizing adverse environmental impact.

3. Several DMRP work units have been designed to investigate improved facility design and construction and to investigate concepts for increasing facility capacities for both economic and environmental protection purposes. However, the total picture would be incomplete without considering methods to more accurately determine the in situ (predredging) volume of dredged material that can be placed within a containment area. To this end the investigation reported herein was accomplished by the Constructed Facilities Division, Department of Civil Engineering, Massachusetts Institute of Technology (MIT). The MIT personnel made extensive use of the expertise of Corps of Engineers District and Division personnel as well as private dredging consultants.

4. A rational method to size dredged material containment area, as well as guidelines for selecting the parameters required by the method, is

presented in the report. The method considers properties of both channel sediment (before dredging) and dredged material (after disposal) and the effects of the dredging operation. The major unknown determined by the method consists of the void ratio of the dredged material in the containment area. Laboratory sedimentation tests of channel sediment helped predict void ratio versus depth and time in dredged material. Field investigations including measurements of water content, rate of settling, excess pore pressure in the dredged material, and spatial distribution of solids in the containment area provide understanding of the material behavior. The sizing technique was applied to four existing disposal sites and the field measurements compared favorably with the predicted behavior. As a whole, comparisons of the predicted versus measured void ratio distribution of dredged material and the predicted versus observed performance of containment areas were satisfactory.

5. This study is one of several studies initiated by the DMRP to provide guidance on sizing containment areas for both capacity and effluent quality. The guidelines presented in this report should be considered interim. Final guidelines will be based on a synthesis and interpretation of all studies related to the sizing of containment areas.

JOHN L. CANNON
Colonel, Corps of Engineers
Commander and Director

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A rational method to size dredged material containment areas and guidelines for selecting the parameters required by the method are presented. The technique aims at improving the bulking factor sizing method presently in use and takes into account (a) the properties of the channel sediment to be dredged, (b) the behavior of the dredged material in the disposal site, and (c) the components of the dredging operation that affect volume of sediment

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dredged. For these purposes, current practice was surveyed, pertinent values of the dredging operation were reviewed, the behavior of several types of dredged material was investigated, and the prediction methodology was applied to four field cases.

The major unknown in the method is the void ratio of the dredged material in the containment area. Laboratory sedimentation tests on channel sediment help predict void ratio versus depth and time in dredged material. Field investigations, including measurements of water content, rate of settling, excess pore pressure in the dredged material, and spatial distribution of solids in the containment area provide understanding of the material behavior. As a whole, comparisons of the predicted versus measured void ratio distribution of dredged material and the predicted versus observed performance of containment areas were satisfactory.

EXECUTIVE SUMMARY

This report proposes a method to determine the size of area to contain dredged material and provides guidelines for selecting the parameters required by the method. The sizing method considers properties of both channel sediment (before dredging) and dredged material (after disposal) and the effects of the dredging operation. The major unknown in the method consists of the void ratio of the dredged material in the containment area. Laboratory sedimentation tests on channel sediment help predict void ratio versus depth and time in dredged material. Field investigations, including measurements of water content, rate of settling, excess pore pressure in the dredged material, and spatial distribution of solids in the containment area provide understanding of the material behavior. Part V applies the sizing technique to four existing disposal sites and compares field measurements with predicted behavior. As a whole, comparisons of the predicted versus measured void ratio distribution of dredged material and the predicted versus observed performance of containment areas were satisfactory. The last part of the report evaluates the reliability of the prediction technique.

PREFACE

The work described in this report was performed under Contract DACW39-75-C-0074, titled "Engineering Evaluation of Performance of Containment Areas Filled with Dredged Material," between the U. S. Army Engineer Waterways Experiment Station (WES) and the Massachusetts Institute of Technology (MIT). The research was sponsored by the Office, Chief of Engineers (DAEN-CWO-M), under the civil works research program Dredged Material Research Program (DMRP).

The study was conducted at MIT during the period July 1, 1975 - July 31, 1976 under the supervision of Dr. T. William Lambe, Principal Investigator of the research program, and Edmund K. Turner, Professor of Civil Engineering. Dr. Suzanne M. Lacasse and Dr. W. Allen Marr, Research Associates, assisted in the supervision of the project. Messrs. Roger F. Gardner, Matthew J. Barvenik, and Miss Lilly C. Lee, Research Assistants, also made major contributions to the research program. The laboratory and instrumentation expertise provided by Dr. R. T. Martin, Senior Research Associate, is also acknowledged.

The researchers are also grateful for the cooperation obtained from the following staff members of the Corps of Engineers District offices: Mr. L. H. Hair, Chief of Construction Operations, Messrs. G. E. Greener and P. Zernentsch, Operations Division, Mr. J.A. Foley, Chief of Engineering, and Mr. I. Reinig, Engineering Division, all from the USAE District,

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The DMRP is conducted under the general supervision of Dr. John Harrison, Chief, and Dr. R. T. Saucier, Special Assistant for Dredged Material Research, Environmental Effects Laboratory. This work was sponsored by the Disposal Operations Project, Mr. Charles C. Calhoun, Jr., Manager. Dr. T. Allan Haliburton was Contract Manager.

Directors of WES during the study and preparation of this report were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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SIZING OF CONTAINMENT AREAS FOR DREDGED MATERIAL

PART 1: INTRODUCTION

Problem Statement

1. The increasing scarcity and cost of land-based disposal areas for dredged material and restrictions on open-water disposal create an important need for efficient use of existing and future disposal sites. Whereas densification of the dredged material and design of containment areas to maximize settling effectiveness appear as possible means to reduce required containment volumes, the first priority remains the assessment of the volume actually occupied by a given volume of material to be dredged and disposed.

2. Two important variables set stringent conditions on land-based disposal projects: volume of channel sediment, i.e., material to be dredged and available containment volume. The empirical nature of existing sizing methods and the complex geotechnical aspects of channel sediment (before dredging) and dredged material (after disposal) render reliable assessment of performance of a containment area very difficult.

3. Bulking factors have been commonly used to estimate required volume capacity. Expressed as a "ratio of the volume occupied by the dredged material after sedimentation in the containment area to the volume of the in situ channel sediment,"[1] bulking factors for specific types of sediments and for specific locations have been determined on the basis of past experience. A soil with a low density in situ may be assigned

a relatively small bulking factor (0.5), whereas a similar type of soil with a greater in situ density may be assigned a greater bulking factor. References 1 and 2 give bulking factors between 0.5 and 2.3, depending on type of channel sediment (often arbitrarily defined), geographical location, or whether they consider allowances for overdredging or settlement of dredged material in the containment area. Designers need therefore a rational sizing method that includes in a systematic manner the parameters that affect the volume of dredged material in a disposal area.

4. In 1975, MIT developed a method to predict the stable elevation of a marsh created from dredged material.[3] The approach provided an improvement to the existing empirical methods in use but addressed the specific problem of marsh creation. The method integrated various components of the dredging operation through a material balance equation, defining an equilibrium void ratio for the dredged material when excess pore pressures were expected near complete dissipation.

5. Because of high natural water content and successive state mutations from slurry to suspension to soil, dredged material cannot be investigated by traditional means. Depending on the dredging method used, dredged material enters a containment area as a slurry of variable solids concentration or in chunks transported by water. It then settles in the area, leading to an increase in solids concentration. Prior to

the present research, very little literature on the sedimentation and/or consolidation behavior of dredged material was available. Results of tests in this report will show that the change in void ratio with stress is nonlinear, even on a semilogarithmic plot.

6. Other elements of concern included the effects of successive dredging operations, entrance and exit velocity in the disposal area, and possible segregation of particles; all these considerations added to the complexity of the problem. The sizing method developed in this research integrates all the important components of a dredging operation *affecting* the volume occupied by dredged material in a disposal area.

Purpose and Scope of Research

7. The primary goals of this research were to:

a. Propose a methodology to predict the volume occupied by a given volume of channel sediment to be deposited in a containment area. The methodology provides specific (and simple) procedures for a sizing technique more reliable than the bulking factor method.

b. Give guidelines for selection of parameter values required in the prediction methodology.

c. Investigate the time-dependent behavior of dredged material. Geotechnical properties measured in the laboratory and in the field provide insight in the performance to be expected in future containment areas.

d. Apply the prediction methodology and evaluate its reliability.

8. In order to present the results of this research, the report first identifies the important variables affecting performance. After summarizing the practicians' opinion on the importance and numerical values of each variable, Part II reviews the sizing techniques used by several experienced offices and research institutes concerned with dredging and proposes the new prediction methodology. Part III details the geotechnical properties of several dredged materials, as measured in the laboratory and in the field. This information shows behavioral trends of dredged material and assists in the development of guidelines for selection of the methodology parameters. Part IV discusses field observations of variables related to the dredging operation. In Part V, four existing disposal sites serve as examples of possible application of the methodology. In two cases, the predicted behavior is checked with the actual field performance and therefore helps evaluate the prediction technique. The four sites examined include: Disposal Area nos. 1 and 12 in Cleveland Harbor, Ohio; Branford Harbor, Connecticut; and Anacortes, Washington. Part VI provides guidelines for selection of sizing methodology parameters and Part VII presents recommendations with respect to application of the prediction method.

PART II: CONTAINMENT AREA SIZING METHODOLOGY

Introduction

9. The MIT marsh creation sizing method quantified, where possible, the interrelationships among the components of a dredging project that affect volume predictions.[3] Use of the prediction methodology required knowledge of:

   a. The efficiency of the dredging operation (loss or gain of solids).

   b. The engineering characteristics of sediment and dredged material.

The methodology appeared workable, provided the significant variables in the problem were properly identified and their relative importance assessed. This part of the report extends the MIT procedure and provides a sizing methodology for containment areas filled with dredged material.

Review of Current Sizing Methods

10. In order to obtain a survey of current sizing methods, the authors interviewed selected dredging specialists with respect to their sizing practice. Table 1 lists the offices consulted and describes their respective techniques. The majority of the offices consulted used a refined but still empirical bulking factor technique where sizing depends on a factor defined in terms of the grain size of the sediment. Table 1 gives sizing factors indicated by each organization.

Table 1

Summary of Sizing Methods Used by Selected Corps of Engineers District Offices and Research Agencies

Source of Information	Containment Sizing Factor to Include*: 1	2	3	4	5	6	7	Material Type	Sizing Factor**	Comments
Buffalo District	✓				✓	✓	✓	Sand Clay & silt	1.0 0.5-1.0	-Uncertainty on volume dredged -Observed sizing factor in Cleveland, Ohio, for organic silts: 0.79
Norfolk District	✓	✓					✓	Sand Clay & silt	1.0 2.0	-Factors generally overpredict required containment size
Mobile District	✓	✓	✓					All types	1.2	-Conservative method (long term) -No losses during removal and transport assumed
Detroit District	✓				✓	✓		Sand & silt	0.6-1.0	-Past volume predictions both over- and underpredicted volume -15% swell upon bottom removal -50 to 85% reduction in volume
New England Division	✓							All types	1.25	
Seattle District	✓						✓	Sand Silt Clay	1.1 1.3 1.5	-Sizing factors based on field observations -Use weighted average sizing factor
Philadelphia District	✓				✓	✓	✓	Sand Silt Clay	0.56 0.73 1.0-1.12	-Factors without settlement allowances are 1.0, 1.3, and 1.8-2.0 for sand, silt, clay -Settlement estimates based on field observations and column sedimentation tests in 6-cm ϕ 50-cm high cells
Galveston District	✓				✓		✓	Silt Clay	1.35 1.65	-One yr after disposal, consider that settlements have reduced volume by ≃50% -Method does not apply to sand
Jacksonville District	✓						✓	Sand Clay	1.2-1.3 2.0	
J. Huston, Dredging Consultant	✓	✓					✓	Sand Silt Clay Sandy clay Rock & gravel	1.0 1.5 2.0 1.25 1.75	-Use weighted average sizing factor
Japan Dredging & Reclamation Eng. Assoc., Tokyo	✓				✓			Sand Silt Clay	1.0 1.3-1.6 2.0	-Settlement prediction of clay very unreliable -Use laboratory tests to obtain factors
Port & Harbour Technical Research Institute, Tokyo	✓				✓	✓	✓	Sand & silt	0.7-0.9	-If swell factor only, use 1.3 -Factors based on case studies -Use laboratory sedimentation tests to obtain factors

*(1) Volume of In Situ Channel Sediment
(2) Overdredging
(3) Transport Efficiency
(4) Containment Area Losses
(5) Consolidation of Dredged Material in Containment Area
(6) Containment Area Foundation Settlement
(7) Description of Material

**Sizing Factor = Ratio of volume of dredged material in containment area to volume of in situ channel sediment

These factors express the ratio of the volume occupied by the dredged material in the containment area to the volume of sediment removed from the channel bottom. Ninety percent of the individuals consulted indicated that their numbers were based solely on experience.

11. Classification of materials as sands, silts, or clays needs further emphasis here. In this report, sands include grain sizes coarser than the US Standard no. 200 sieve. Silts describe materials with particle sizes ranging from 0.074 mm to 0.002 mm. They plot below Casagrande's A-line on the plasticity chart.* Clays include the finer-particle material and plot above the A-line. This classification, although very primitive, permits one to distinguish behavioral trends. However, in nature, soil comes often as a combination of these soil types, and careful judgment must be exercised when applying any correlation between grain-size and soil property.

12. Two volume components need consideration: during the dredging operation, the bottom sediment swells; after disposal, the material consolidates under its own weight, thus creating more storage volume. The agencies consulted consider either or both of these effects and define their sizing factors accordingly. Whereas nearly all methods use a swell factor, less than half the agencies use an estimate of the settlement of the dredged material. Sole consideration of the swell of

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*See Reference 4, for definition and application of plasticity chart.

dredged material can not predict adequately the volume in the containment area except for volume immediately after disposal time. An approach considering settlement with time of the material should be more satisfactory. It becomes therefore necessary to estimate the properties of the material as a function of time: for example, the volume occupied by the dredged material after each yearly operation, in the case of a containment area designed for a multi-year usage. Time for settlement compared to frequency of successive dredging operations will be discussed in Part III and introduced in the prediction methodology.

13. The individuals who provided the factors in Table 1 stated that their sizing method had generally been rather unreliable, at times undersizing areas by as much as 50 percent, and at other times, oversizing them by as much as 100 percent. Results seem to have been slightly more satisfactory for sandy sediments, where particles settle out and reach end-point density rapidly. Clays have a much more complex behavior pattern, with slower settling rate, slowly dissipating excess pore pressures, and nonlinear consolidation. One can also expect more solids losses during dredging of fine materials. The reliability of the sizing methods commonly used in the case of finer material has not been good. The numbers presented in Table 1 remain very subjective: obvious shortcomings include the difficulty in obtaining a unified material classification from all specialists and the impossibility to

normalize dredgers' experiences.

14. A brief comment should be added here with respect to the sizing practices in Japan where dredging for land creation is practiced on a long-term basis with low priority on proper containment size prediction. As presented in Table 1, volume-ratio laboratory sedimentation tests are used to compare volume of dredged material to initial sediment volume. Settlement measurements in small-scale sedimentation cells, are taken 48 hours after pour. As a rule-of-thumb, a sizing factor including both swell and settlements averages 1.00 for sands and silts. Bulking factors associated with swell only go from 1.30 to 2.00 for silts and clays, whereas settlement factors vary from 0.68 to 0.90.

15. Generally, the Port and Harbour Technical Research Institute size containment areas for dredged material in the following manner:

- a. For a given volume of sediment, apply the appropriate swell factor, function of grain size.
- b. Estimate the volume decrease due to self-weight settlement of the material under study.
- c. Consider any settlement of the foundation in the containment area.
- d. Calculate the volume required to contain the dredged material.

This method does not consider losses in the dredging operation. However, in three instances, overall losses were backfigured[5] after completion of the job and proved important (see Part IV).

Prediction Methodology

16. The proposed methodology proceeds in five steps:

- a. Determination of volume of solids effectively retained in the area through a material balance equation.
- b. Prediction of state of dredged material in area (void ratio).
- c. Prediction of required containment volume for dredged material.
- d. Computation of settlement of foundation.
- e. Computation, if required, of containment area dimensions.

The chart in Figure 1 outlines the step-by-step procedure described below.

17. The design volume of material to be dredged is determined by field investigations, past yearly records, or channel depth requirements. Assessment of the in situ sediment void ratio, e_o*, from field investigation and/or correlations, will yield the design volume of solids to be dredged, since the relationship between volume of solids dredged and total volume of sediment removed is:

$$V_p = \frac{V_t}{1 + e_o} \qquad (1)$$

where V_p = design volume of solids to be dredged

V_t = design volume of bottom sediment to be dredged

*For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix B).

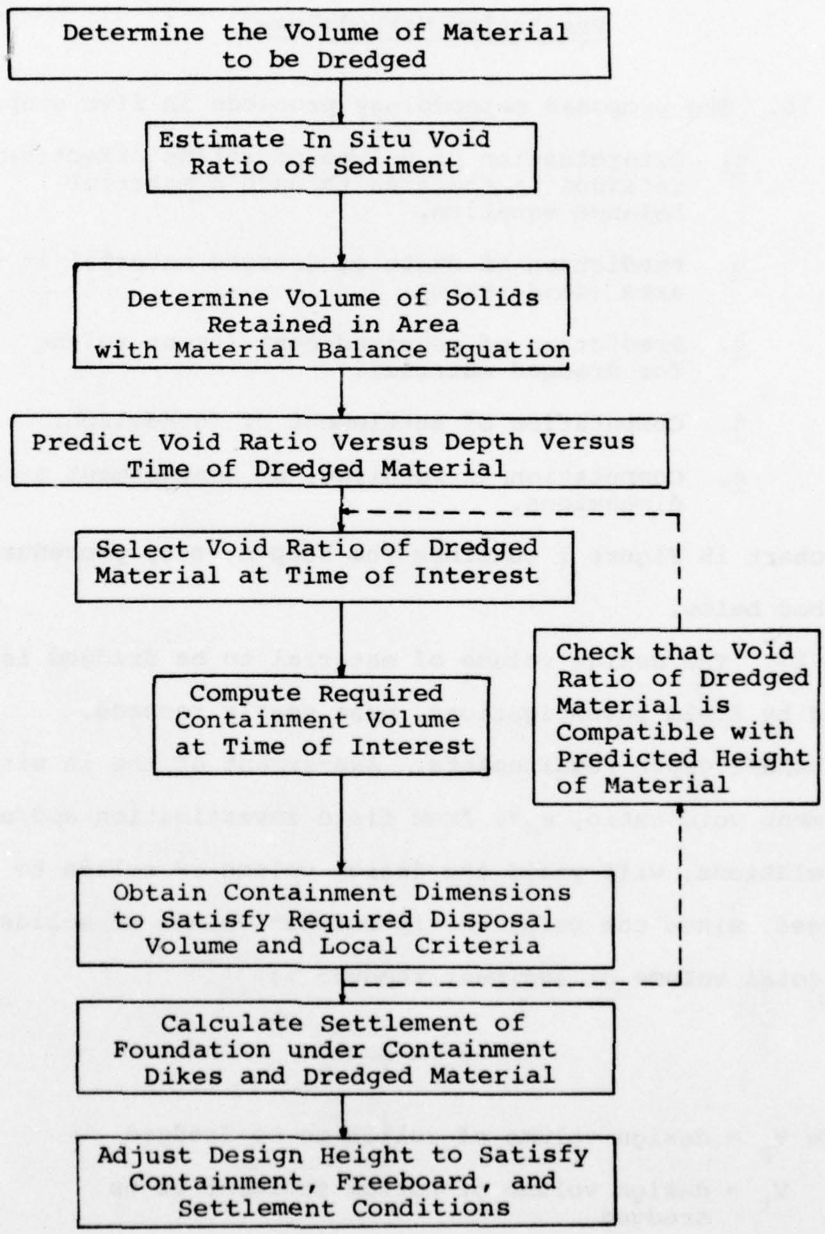


Figure 1. Procedure for sizing containment areas

e_o = void ratio of channel sediment.

18. A material balance equation[3] ties in all the components of the dredging process that affect volume by stating that the volume of solids in the containment area equals the volume of solids removed from the bottom minus losses:

$$V_c = V_p(1 + F_o)F_eF_pF_c \tag{2}$$

where V_c = volume of solids retained in containment area

V_p = design volume of solids to be dredged

F_o = overdredging factor

F_e = efficiency of dredge removal action

F_p = efficiency of transport system

F_c = efficiency of containment system

The total volume of in situ solids removed includes possible *overdredging by the contractor and is related to the design* volume of solids to be removed, V_p, by the factor $(1 + F_o)$.

19. Efficiencies in Equations 1 and 2 express the ratio of volume of solids delivered by each component to volume of solids input to that component. For example, F_e includes losses of material upon removal of sediment* and F_c, possible losses of material through the containment system and over the effluent weir (pumping rates for small areas can then become important).

20. The state of the dredged material in the disposal area represents another variable required to estimate the required containment volume. The sizing methodology predicts

*Pertains to all types of dredging actions (mechanical, suction, or combined).

the void ratio versus depth distribution of the dredged material as a function of time. The void ratio versus depth distribution of dredged material at a given time yields an average void ratio over a trial depth. The required containment volume for this time frame can then be expressed as:

$$V_{CA} = V_c(1 + e_{ave}) \tag{3}$$

where V_{CA} = required containment volume

e_{ave} = average void ratio of dredged material

Substituting Equations 1 and 2 in Equation 3, the required containment volume becomes:

$$V_{CA} = \frac{V_t(1 + F_o)F_eF_pF_c(1 + e_{ave})}{(1 + e_o)} \tag{4}$$

Given an area available for disposal, the height of the dredged material at an average void ratio, e_{ave}, can be calculated. For given restrictions on maximum elevation, the size of the required containment facility for a given volume of dredged material can be obtained.

21. The next step in the methodology involves checking that the average void ratio for dredged material over a trial depth remains compatible with the predicted height of the containment facility. For short-term predictions this verification is generally perfunctory since laboratory and field observations will show that void ratios remain fairly constant or decrease very slowly below a depth of 25 cm.

22. In the case of thick deposits of dredged material, settlement of the underlying foundation might occur and alter

the disposal site capacity. In some cases, foundation settlements can be so small that neglecting them in the computations would not have appreciably impaired the predictions.[3,5,6] Moreover, if erection of the containment dikes is recent, the dikes themselves may settle. Consideration of the two components of settlement remains therefore essential.

Parameters

23. Table 2 indexes the physical components considered in the sizing methodology, lists the significant parameters and the means available to assign numbers to the parameter, and indicates where such information can be found in the report.

Dredged material characteristics

24. Only the average void ratio versus depth at a given time is required for solving Equation 4. This parameter involves knowledge of other characteristics such as grain size, plasticity, sedimentation-consolidation rate, etc. Several means exist to determine these properties, as listed in Table 2, but since one of the goals of the present study is devising reliable and simple methods, the report provides correlations developed in this research, based on all laboratory and field measurements available (see Parts III and VI).

Sediment characteristics

25. The in situ void ratio, e_o, and the design volume

Table 2

Index to Sizing Methodology Parameters

Physical Component	Parameter	Determination	Report Section
Dredged Material	Average void ratio, e_{ave} (vs depth and vs time)	Past experience	
		Best estimates	
		Laboratory tests	Part III
		Field measurements	Part III
		Correlations	Parts III, V
Sediment	In situ void ratio, e_o	Experience	
		Channel sampling	
		Correlations	Parts III, V
	Volume of material dredged, V_t	Channel surveys Yearly averages Physical requirements	Parts IV, V
Dredging Operation	Overdredging, F_o Removal efficiency, F_e Transport efficiency, F_p Containment efficiency, F_c	Experience Past case studies Best estimates Field measurements and control	Part IV
Foundation Performance	Settlement, ρ_{fdt}	Std 1-D settlement analysis	Part V
		Stress increase due to dredged material surcharge	Part III

of sediment to be dredged are required by the methodology and generally proceed from field investigations prior to dredging or from the designer's past experience. Sampling of sediment remains important since it allows determination of index properties for the dredged material. In situ void ratios measured on various sediment samples are presented in Part III and recommendations for their selection are given in Part VI.

26. It is important to determine with reasonable accuracy the volume of material to be dredged, since the predicted required containment volume is directly proportional to V_t (see Equation 4). Traditionally, this volume has been obtained through surveys (soundings, in most cases); good quality work is essential for reliable predictions. If one wants to check application of the methodology, recording of the volumes of material effectively dredged (through flow meters, displacement of hopper dredges, and/or surveys after job completion) becomes essential.* When possible, this verification will be done in the methodology applications presented in Part V.

Dredging operation parameters

27. The dredging operation parameters include overdredging, F_o, and efficiencies at the mouth of the dredge, F_e, during transport, F_p, and in the disposal area, F_c. Part IV will present values for these parameters and case studies in Part V will provide data that substantiate these factors.

*This procedure also eliminates uncertainties with respect to F_o and F_e.

28. Another dredging operation parameter, which affects the required containment volume but does not appear in Equation 4, is the solids concentration during disposal. In that the solids concentration underlies the determination of void ratios for dredged material,[3] the dredging method is an important factor. Since estimates and field measurements of the solids concentration condition the validity of column simulation tests, they are presented in Part IV.

Foundation performance

29. Determination of the foundation settlement should be fairly straightforward, using conventional techniques. Examples of calculations will be given in Part V.

Time Constraints

30. Two types of containment areas are commonly used:

a. Containment areas filled in one continuous operation.

b. Containment areas designed for multiple-year usage.

The assessment of the state of the dredged material necessitates, in each case, knowledge of the behavior of the dredged material with time. More specifically, how do void ratios change in a given interval of time and how significant is this change until the next filling period?

31. First required is knowledge of periods and frequency of filling. This may vary with local specifications or

practice and with weather conditions. For areas filled in only one operation, column sedimentation tests were used to duplicate the filling action and ensuing settling.[3] For containment areas designed for multiple year usage, knowledge of the successive states prior to each filling and especially prior to the last filling is required. Assessment of the void ratio-effective stress and void ratio-time relationships becomes therefore fundamental. Field and laboratory measurements have made it possible to propose an engineering estimate of these relationships, presented in Part III and applied in Part V. Recommendations for selection of void ratios are presented in Part VI.

Summary

32. The methodology for predicting the size of containment areas filled with dredged material establishes an interrelationship between measurable soil characteristics and dredging operation parameters. A material balance equation determines the effective volume of solids entering the containment area and yields the required containment volume. This part has discussed the various parameters in general terms. The analysis must also consider whether sedimentation will effectively occur during the expected retention time in the confining area. For example, the containment area must be of sufficient length to allow sedimentation of the suspended solids before decantation of the water over the weir.

33. The proposed prediction methodology incorporates the following parameters:

- a. Volume of sediment to be dredged.
- b. In situ void ratio of sediment.
- c. Overdredging factor.
- d. Loss factors in the dredging and disposal operation.
- e. Rate of filling the containment area versus effluent detention time.
- f. Average void ratio versus depth (and total unit weight) of dredged material at a given time.
- g. Foundation settlement.

PART III: BEHAVIOR OF CHANNEL SEDIMENT AND DREDGED MATERIAL

Introduction

34. Very little data have been published on geotechnical properties of dredged material. However, a few sources[3,5,7,8,9,10] present index properties and simplified behavioral patterns. This part details the properties of dredged material measured in the MIT Soil Mechanics Laboratory and in the field at several disposal sites throughout the United States. Comparison with available characteristics of other dredged materials will be made when applicable. Part III of the report is divided into seven sections:

- a. Index properties of the various dredged materials under study.
- b. Void ratio of the channel sediment.
- c. Spatial distribution of solids in disposal sites.
- d. Total unit weight of dredged material.
- e. Rate of settling of dredged material.
- f. Excess pore pressures in dredged material.
- g. Void ratio versus depth distribution in the disposal site.

35. Since the volume change of fine soils upon dredging can be substantial compared to that of sands, only fine-grained materials were investigated. The materials came from seven disposal sites: Cleveland Harbor, Ohio; Branford

Harbor, Connecticut; James River-Windmill Point, Virginia; Capsante, Washington; Anacortes, Washington; Browns Lake, Vicksburg, Mississippi; and Upper Polecat Bay Disposal Area, Mobile, Alabama. Appendix A describes the general layout and the exploratory program at each site.

Index Properties of Dredged Material Under Study

36. Table 3 describes materials from seven sites under study and lists their specific gravity of solids and Atterberg limits. Average values are shown along with the ranges measured for each parameter. Unless otherwise noted, all averages are based on at least ten determinations (in fact, many values in the table represent averages of more than 30 data points). Grain sizes, water contents, void ratios, and ambient water conductance will be presented in the next sections.

37. Cleveland Harbor allows an interesting application since sediment dredged from Lake Erie and Cuyahoga River was disposed in the now combined area nos. 1 and 2 until 1967; since 1974, the material has been placed in area no. 12, where the authors, with the assistance of the Buffalo District office and the Cleveland field office, performed an extensive field investigation. This site provided information on the behavior of both the recently deposited dredged material and material disposed several years ago. Table 3 shows a noticeable difference in the Atterberg limits of the sediment and the dredged material. The material deposited in area nos. 1

Table 3

Index Properties of Dredged Materials at Study Sites

	Specific Gravity of Solids, G_s	Liquid Limit, w_l	Plasticity Index, I_p	Liquidity Index, I_l	Source of Information
Cleveland Harbor:					
1. sediment*: dark grey organic silty clay (OL)	2.66	46 (28.5-57)	19 (8-27)	1.31	MIT Buffalo District
2. dredged material**: very soft organic plastic silty clay, trace of fine sand (OH)	2.66	73 (44-99)	38 (17-53)	----	MIT Buffalo District
Branford Harbor+: brown soft plastic organic clay, some shells (MH-OH)	2.66	95 (51-140)	54 (28-95)	0.98	MIT[3]
James River-Windmill Point: brown organic highly plastic silty clay, trace of sand (CH-OH)	2.66	94 (89-98)	56.5 (55-58)	0.75	MIT References 11 and 12
Anacortes+: medium to stiff highly plastic silty clay, with shells, some sand and gravel (CH)	2.67	72 (2 tests)	44 (2 tests)	----	MIT Seattle District
Capsante+: brown plastic organic silty clay, trace of sand (MH-OH)	2.66	108 (2 tests)	62 (2 tests)	----	MIT
Browns Lake: grey silty clay, trace organic matter, some sand (CL)	2.70	38 (29-47)	14 (8-21)	----	MIT WES
Upper Polecat Bay: dark-grey highly plastic clay, trace of sand, some oil and organic matter (OH)	2.70	90 (53-165)	59 (31-113)	----	WES

*In Cuyahoga River and Lake Erie. +Saltwater environment.

**Dredged material in disposal area no. 1 and 2, seven years after disposal.

and 2 may have been slightly more plastic than the material disposed in area no. 12.

38. The average Atterberg limits results appear in Figure 2 on Casagrande's plasticity chart. All materials plot on or very near the A-line. However, due to the organic content, it is reasonable to expect some scatter in the limits. Figure 3 shows typical grain-size curves at each site, all averages of several determinations. The differences between the 1967 and 1975 Cleveland Harbor materials appear again in the grain-size plot. In Branford Harbor, where both sediment and 10-year-old dredged material were sampled, grain-size distributions remained very consistent. In Anacortes, three types of materials (SM, CL, and CH) were encountered as shown by curves 1, 5, and 9.

Void Ratio of Channel Sediment

39. Table 4 lists the in situ void ratios of channel sediment measured at four sites. The void ratios were computed from the in situ water contents through the equation:

$$e = \frac{G_s w}{S} \tag{5}$$

where G_s = specific gravity of solids

w = water content

S = degree of saturation

e = void ratio

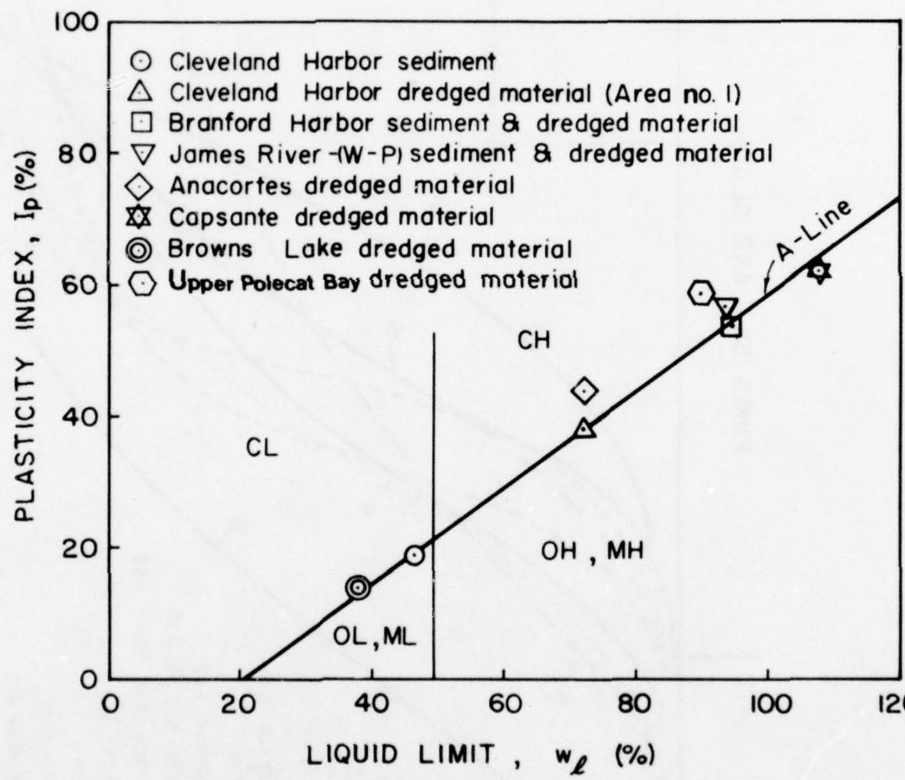


FIGURE 2. PLASTICITY CHART FOR CHANNEL SEDIMENT AND DREDGED MATERIAL

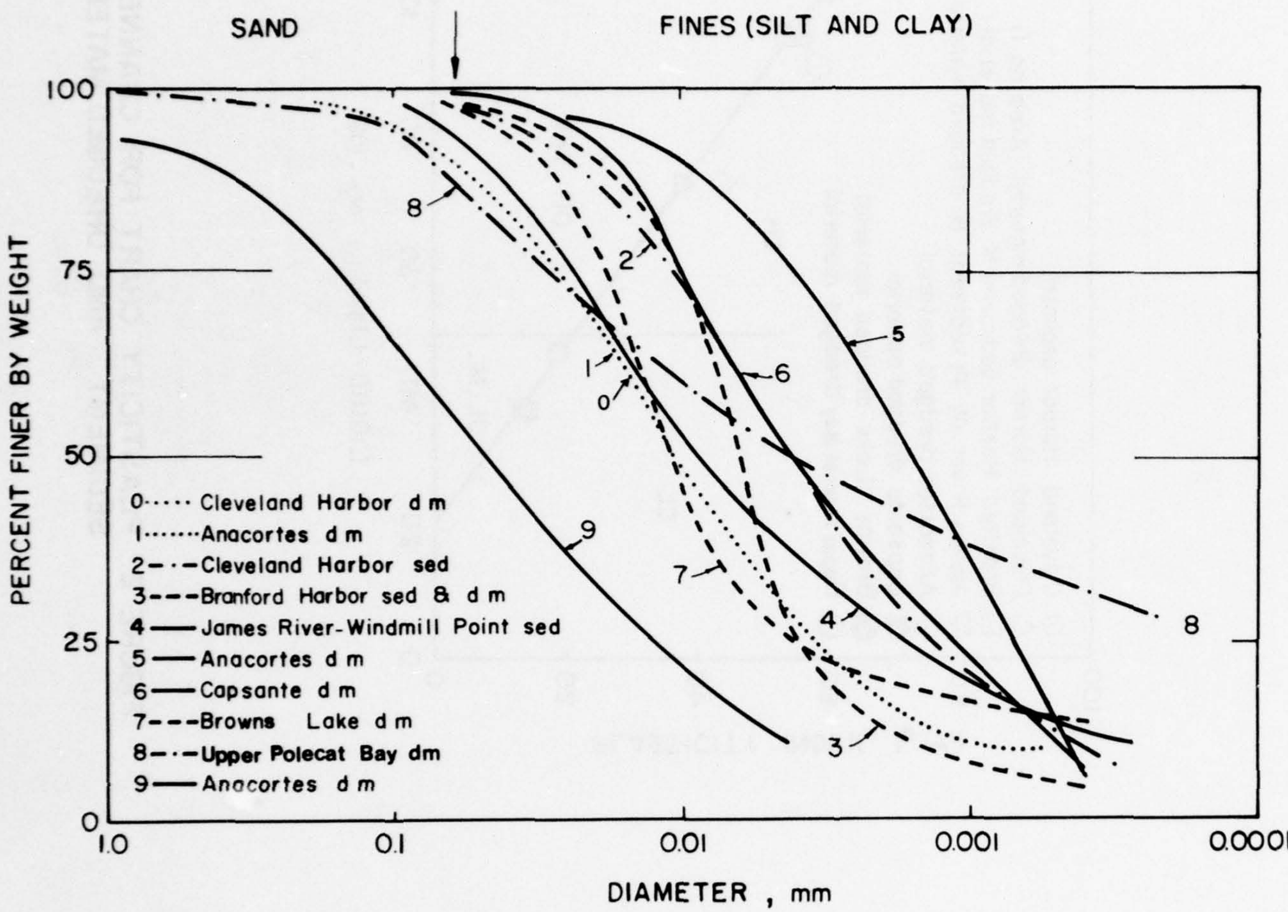


Figure 3. Grain-size distribution of sediment and dredged material

In the case of submerged samples, the degree of saturation was taken as 100 percent. Considerable scatter exists in the values for Cleveland Harbor and Branford Harbor sediments. Probable causes for the scatter in void ratio include sampling difficulty, non-homogeneity of sediment, compression of sample or water gain/loss during coring, extrusion, or transport. The averages shown in Table 4 are based on 20 to 80 measurements in the top 2 m of sediment.

40. Sediment void ratios were also made available to MIT by Japanese specialists.[5] Figure 4 presents the sediment void ratios observed on four materials (numbers 1 to 4) from Sakai Harbour near Osaka. Although only two points of the grain-size curves were available, one can plot approximate grain-size distributions for these materials and their respective measured e_o (through water contents again). Except for one data point ($e_o = 1.9$), the data show lower in situ void ratios for coarser sediments. Combining these data with the previously presented properties of Cleveland Harbor, Branford Harbor, James River-Windmill Point, and Anacortes materials indicates that in situ void ratio increases with increasing percentage of fines and ambient water salinity (see Figure 5).

Spatial Distribution of Solids in Containment Area

41. To illustrate particle segregation of the dredged material[13] in the containment area (due to entrance velocity

Table 4

In Situ Void Ratio of Channel Sediment

Sediment	In Situ Void Ratio Average	In Situ Void Ratio Range	Comments
Cleveland Harbor	2.05	1.00-4.60	0-2 m depths
Branford Harbor*	2.50	1.60-6.20	0-2 m depths, considerable scatter
James River-Windmill Point	2.12	1.60-2.60	0-5 m depths
Anacortes*	0.89	0.61-1.23	Samples taken only in SM material at beginning of operation**

*Saltwater environment

**By depth, values were: 1.18 ± 0.05 at surface
0.84 ± 0.03 at 1.5 m depth
0.64 ± 0.03 at 3 m depth

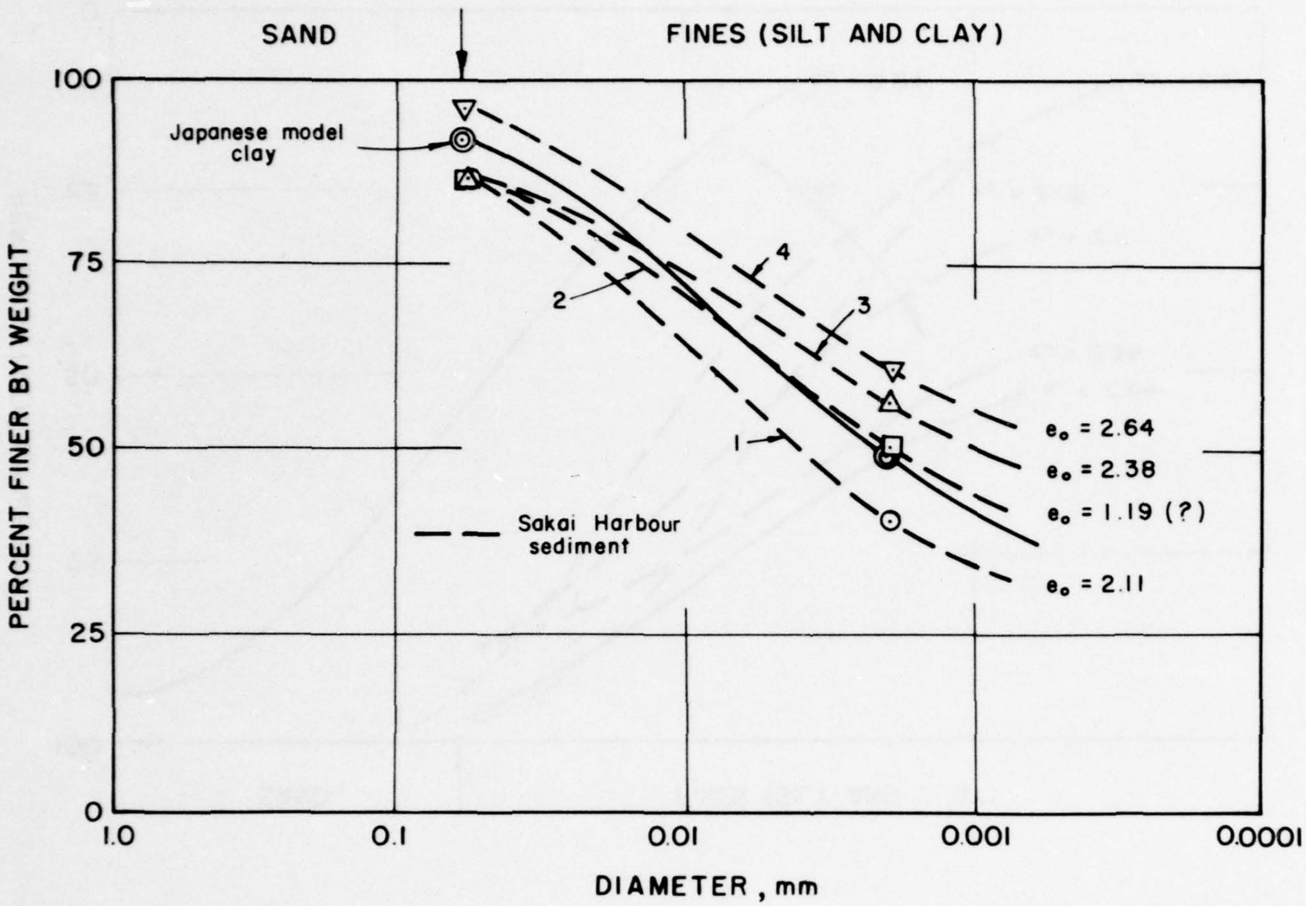


Figure 4. Grain-size distribution and void ratio of four sediments in Sakai Harbour, Japan

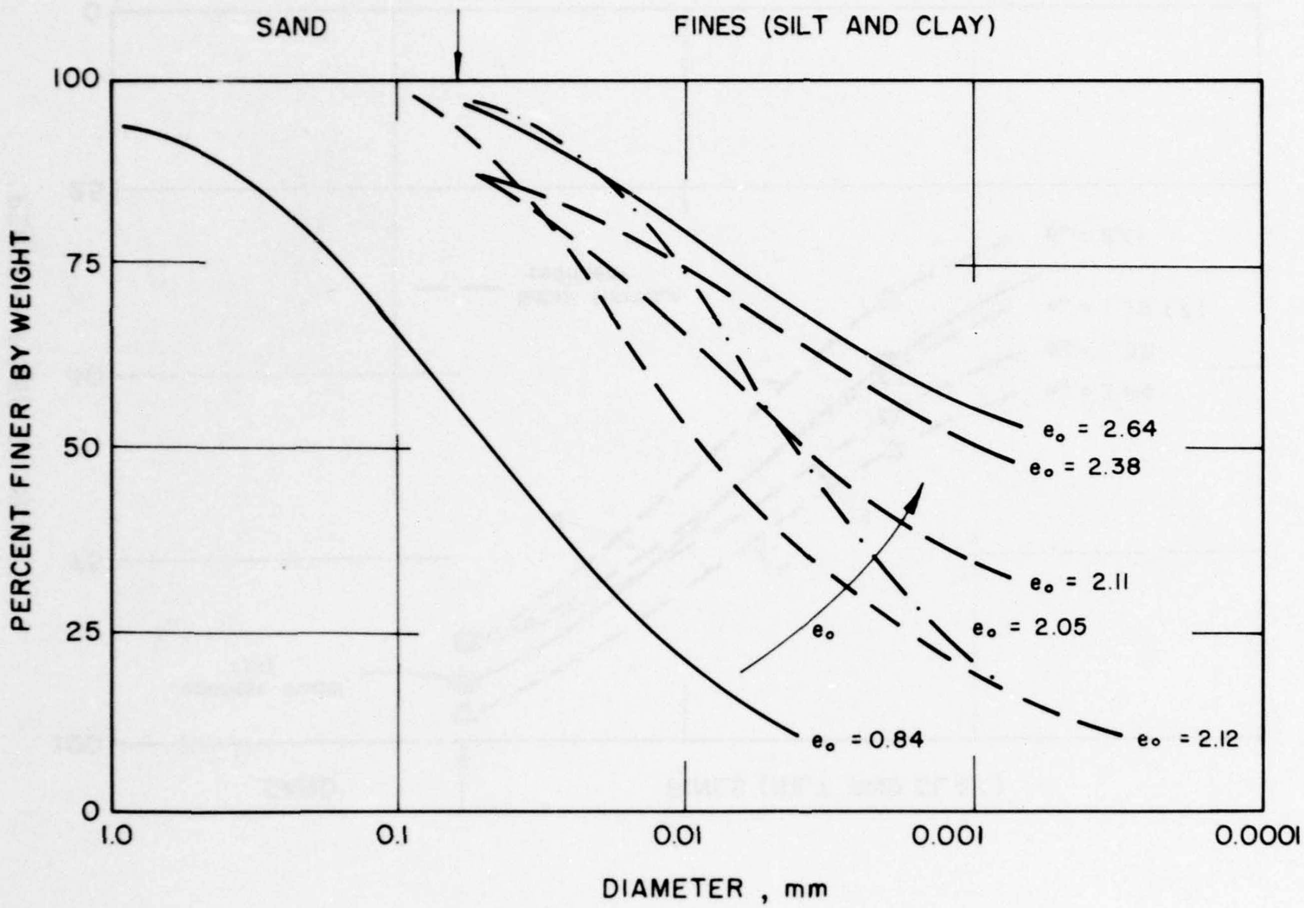


Figure 5. Grain-size distribution and in situ void ratio of sediment

while pumping or to exit velocity generated by the weir discharge), MIT conducted a study of the spatial distribution of solids in several containment areas. The investigation also enabled MIT to answer two questions:

a. How representative of the dredged material deposit are the samples tested in the laboratory sedimentation cells?

b. What disposal area is required to ensure sedimentation of the suspended solids before decantation of the supernatant water over the weir?

Figures 6 through 14 present the results from seven disposal sites: Capsante, Anacortes, Branford Harbor, Cleveland Harbor, James River, Browns Lake, and Upper Polecat Bay.

42. The disposal sites in Capsante and Anacortes (Figures 6 and 7) each have two settling ponds connected by outflow pipes. In Capsante, the effects of increasing distance from the inflow pipe appeared clearly as most of the coarser material was located within 150 m of the source. Away from this point, the samples have nearly identical grain-size curves, except for the southwest corner sample in the primary pond where coarser material had accumulated. All samples were taken at least 15 to 20 cm below the surface. Visual observation at this site as well as at several other sites not mentioned in this study indicated that the coarser material accumulated in a fan-shaped area immediately at the mouth of the inflow pipe. The Anacortes samples (Figure 7) exhibit a similar pattern, except that the samples in the secondary settling pond gave slightly less consistent results. However,

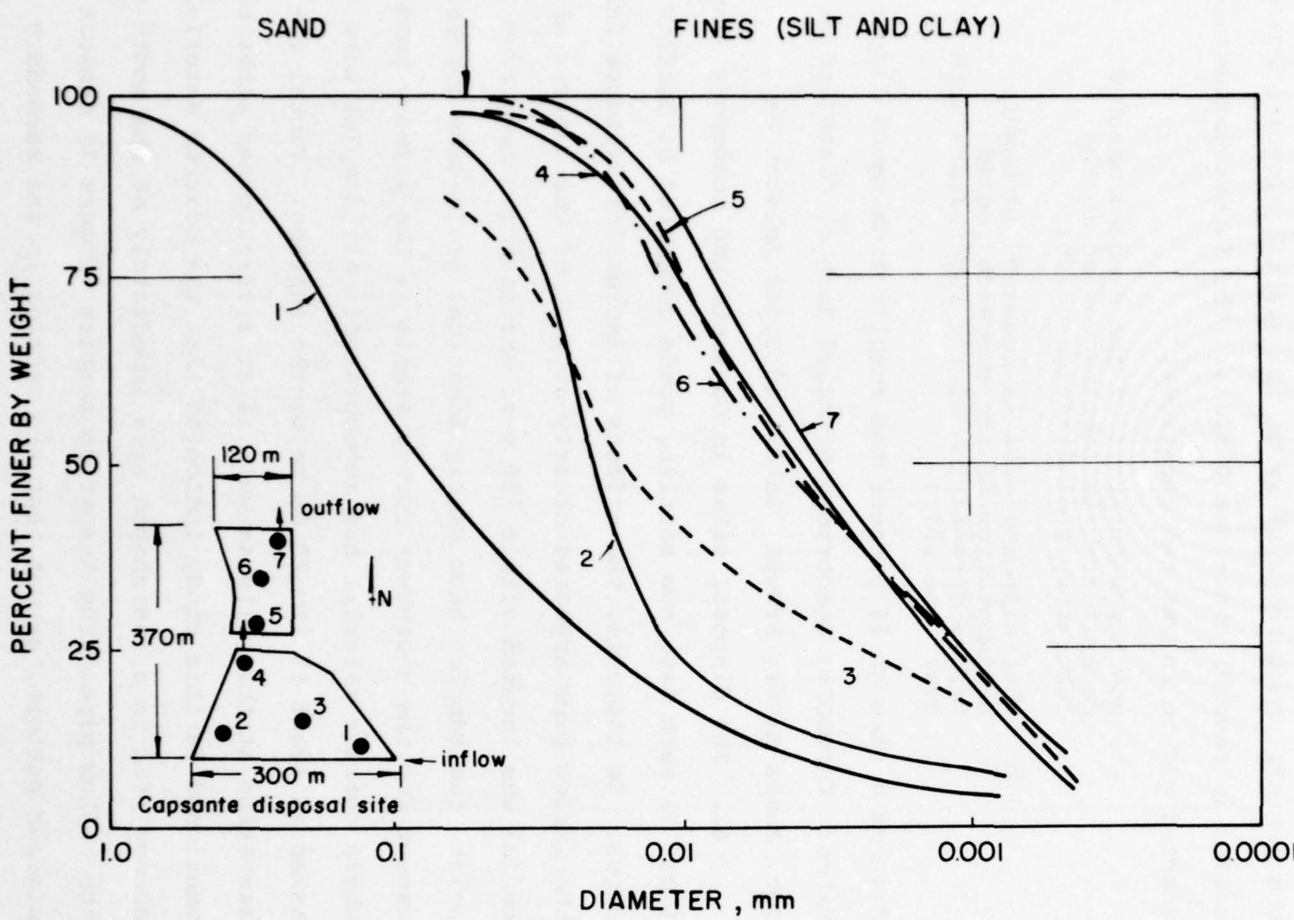


FIGURE 6. SPATIAL DISTRIBUTION OF SOLIDS IN CAPSANTE SITE

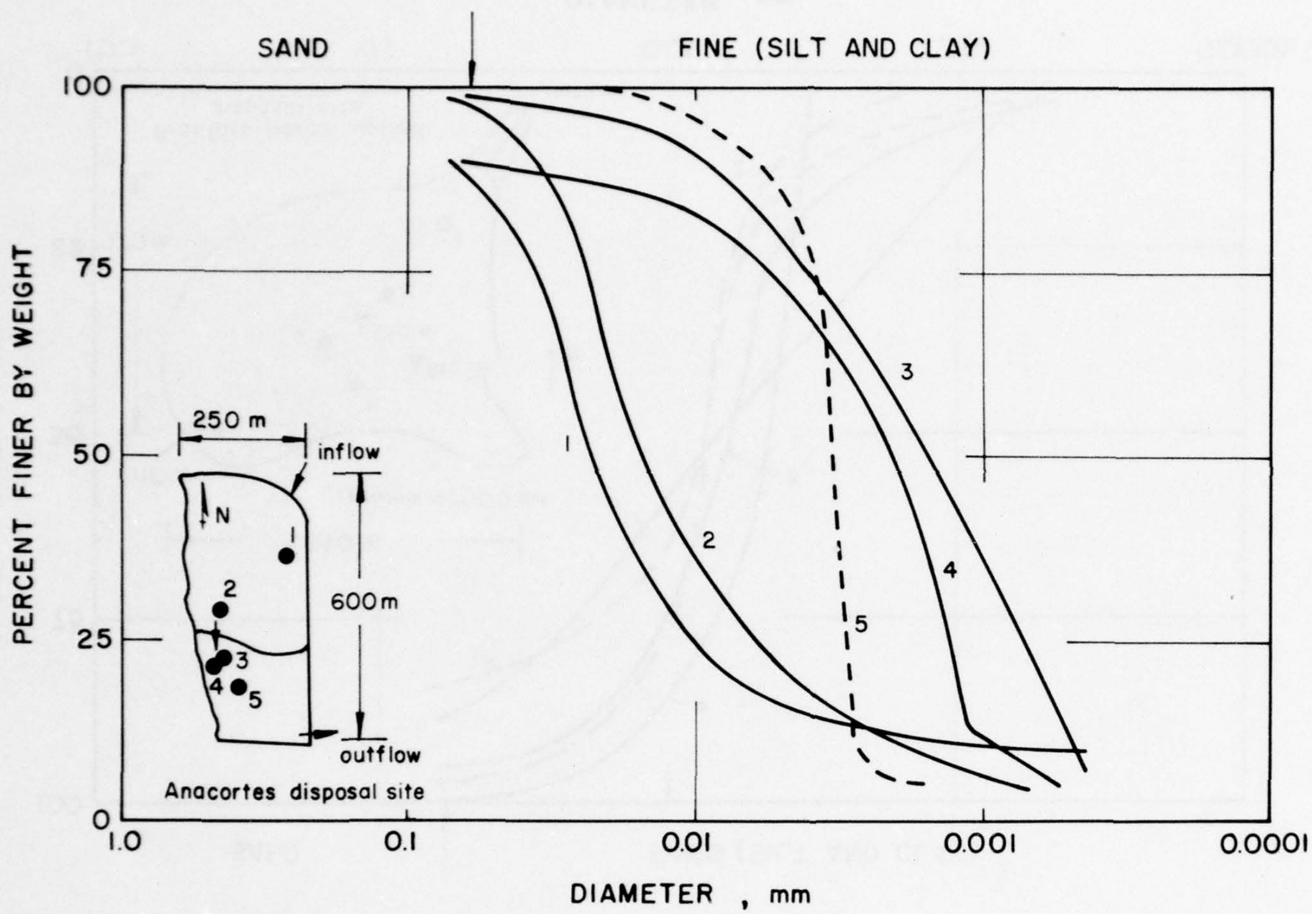


FIGURE 7. SPATIAL DISTRIBUTION OF SOLIDS IN ANACORTES DISPOSAL SITE

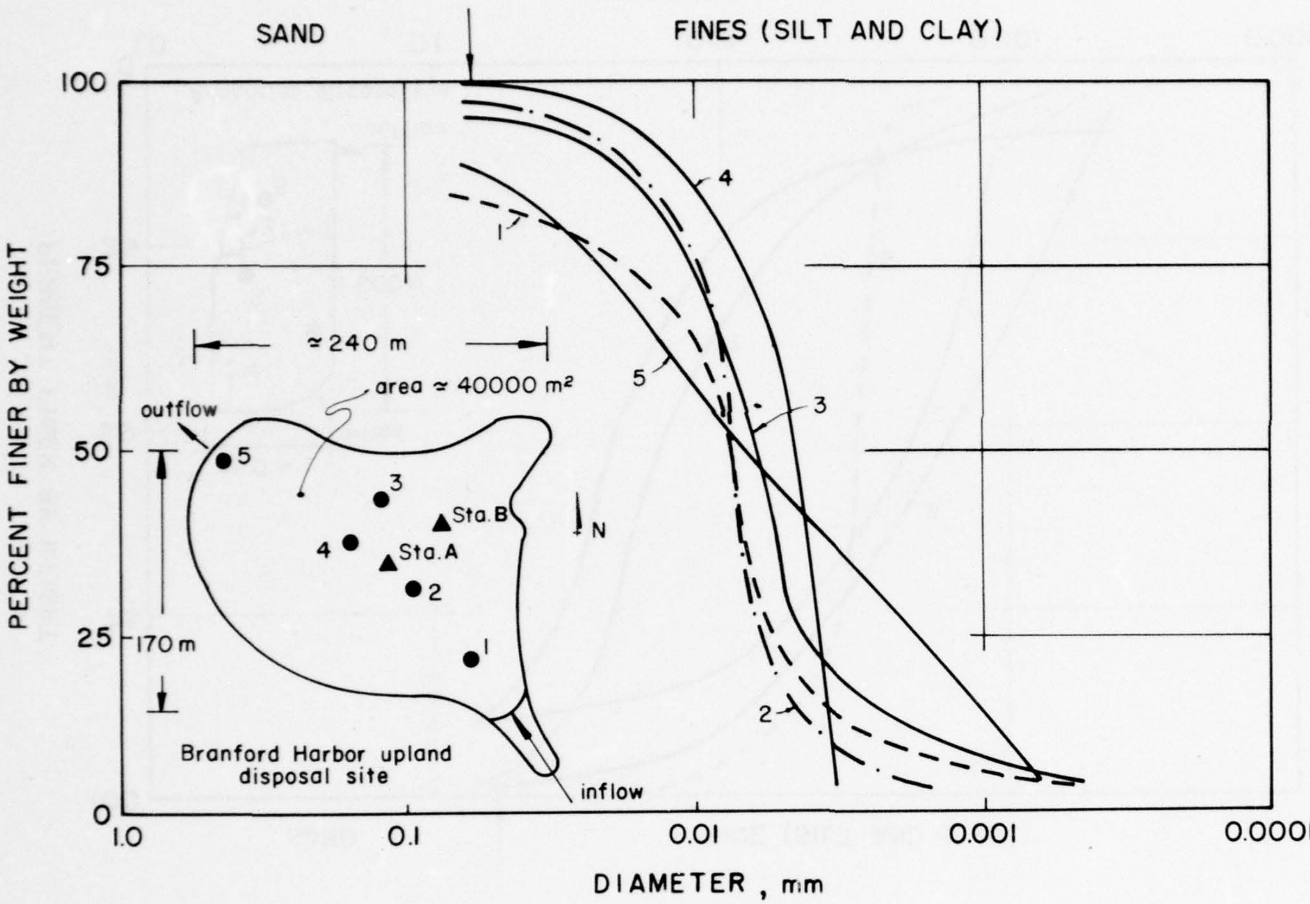


FIGURE 8. SPATIAL DISTRIBUTION OF SOLIDS IN BRANFORD HARBOR SITE

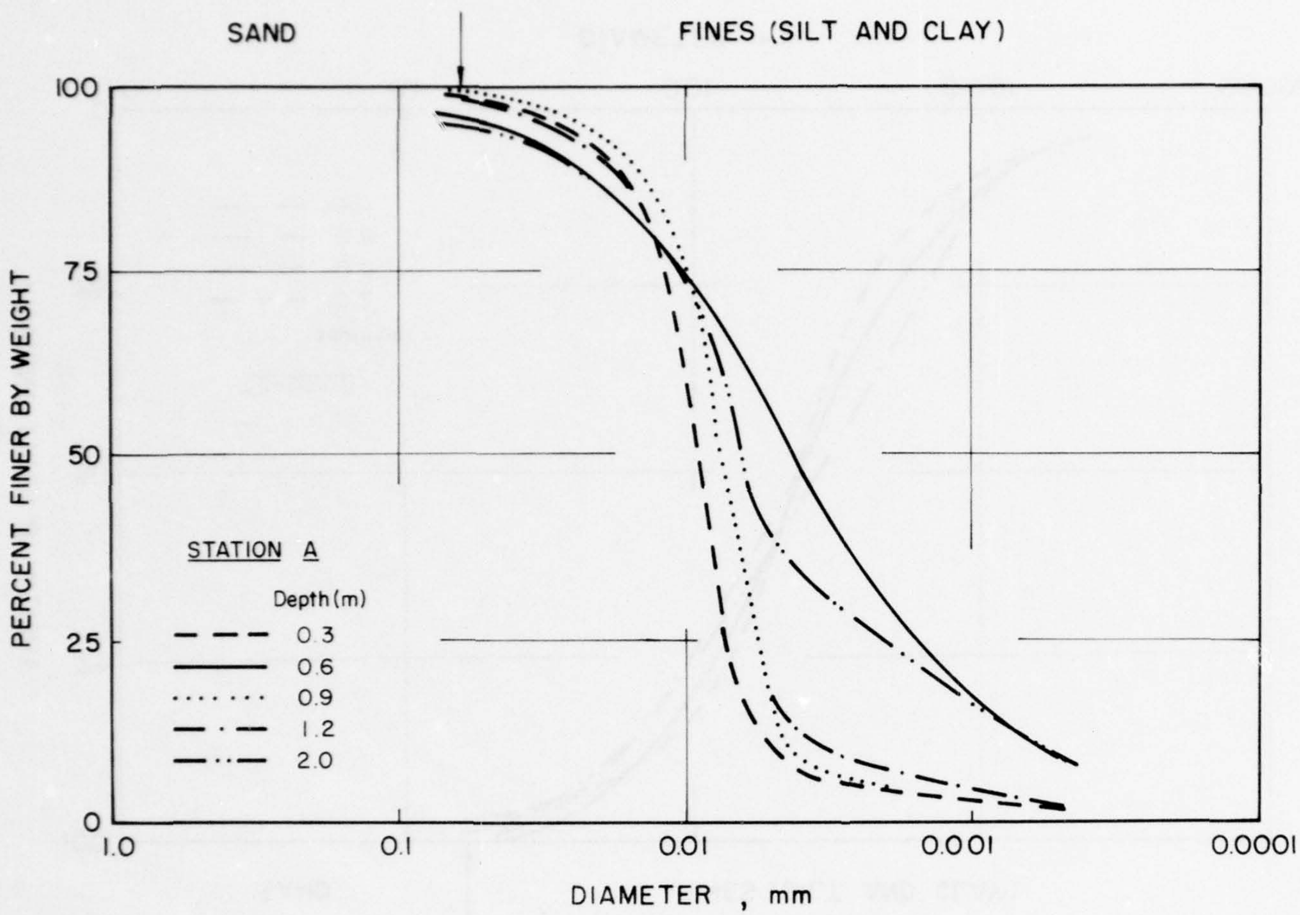


FIGURE 9. GRAIN-SIZE DISTRIBUTION AT STATION A IN BRANFORD HARBOR SITE

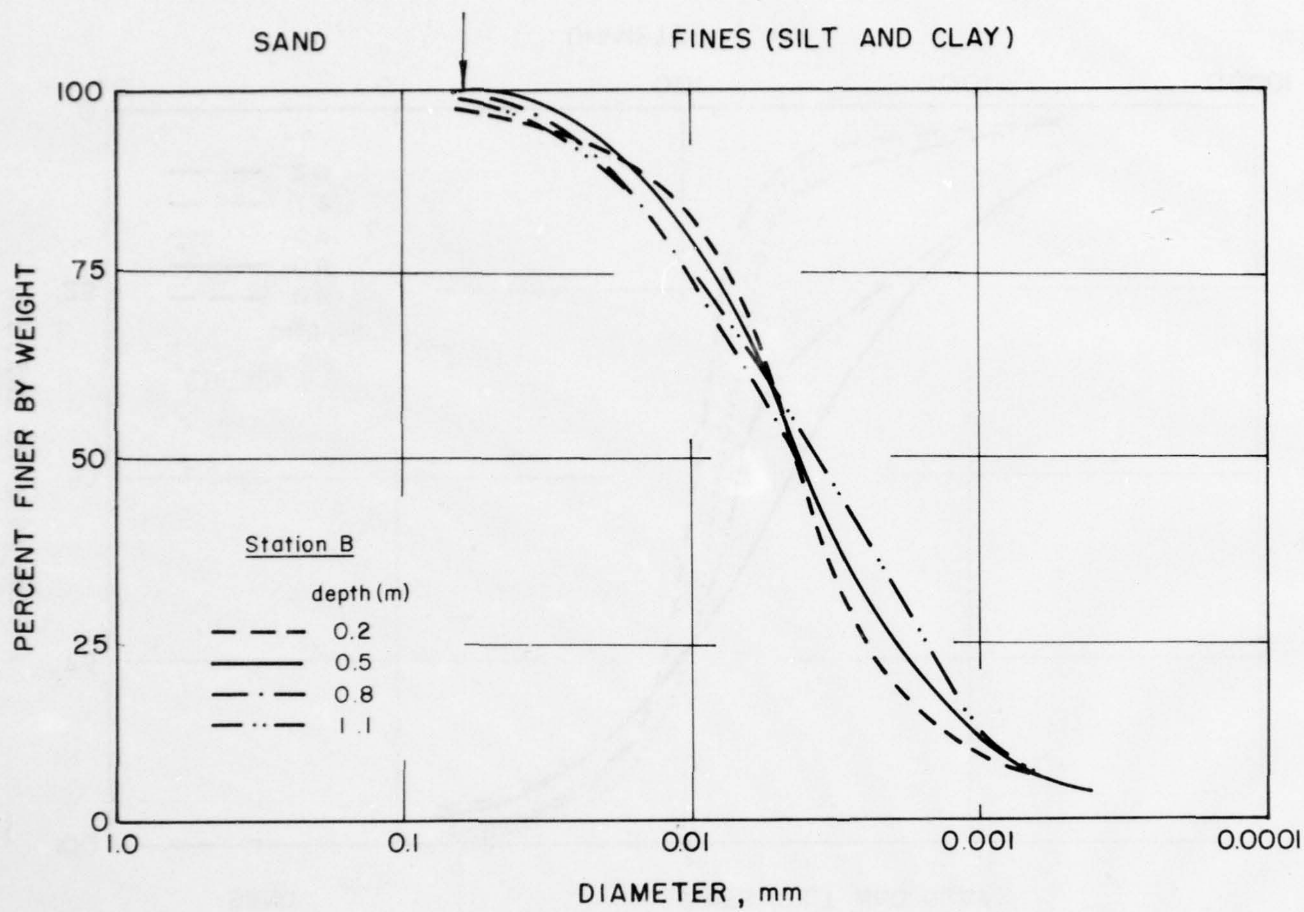


FIGURE 10. GRAIN-SIZE DISTRIBUTIONS AT STATION B IN BRANFORD HARBOR SITE

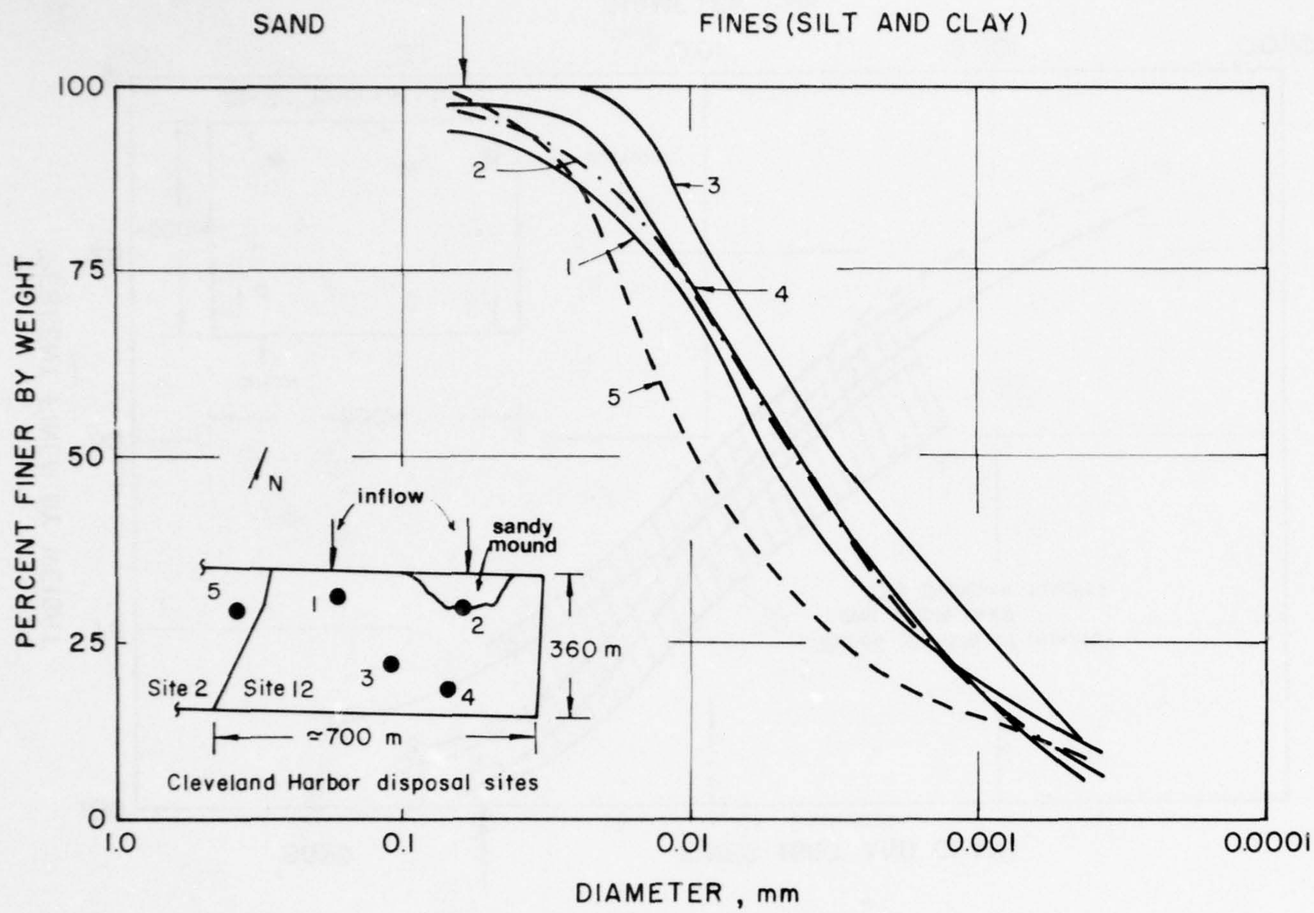


FIGURE 11. SPATIAL DISTRIBUTION OF SOLIDS IN CLEVELAND HARBOR SITE NO. 12

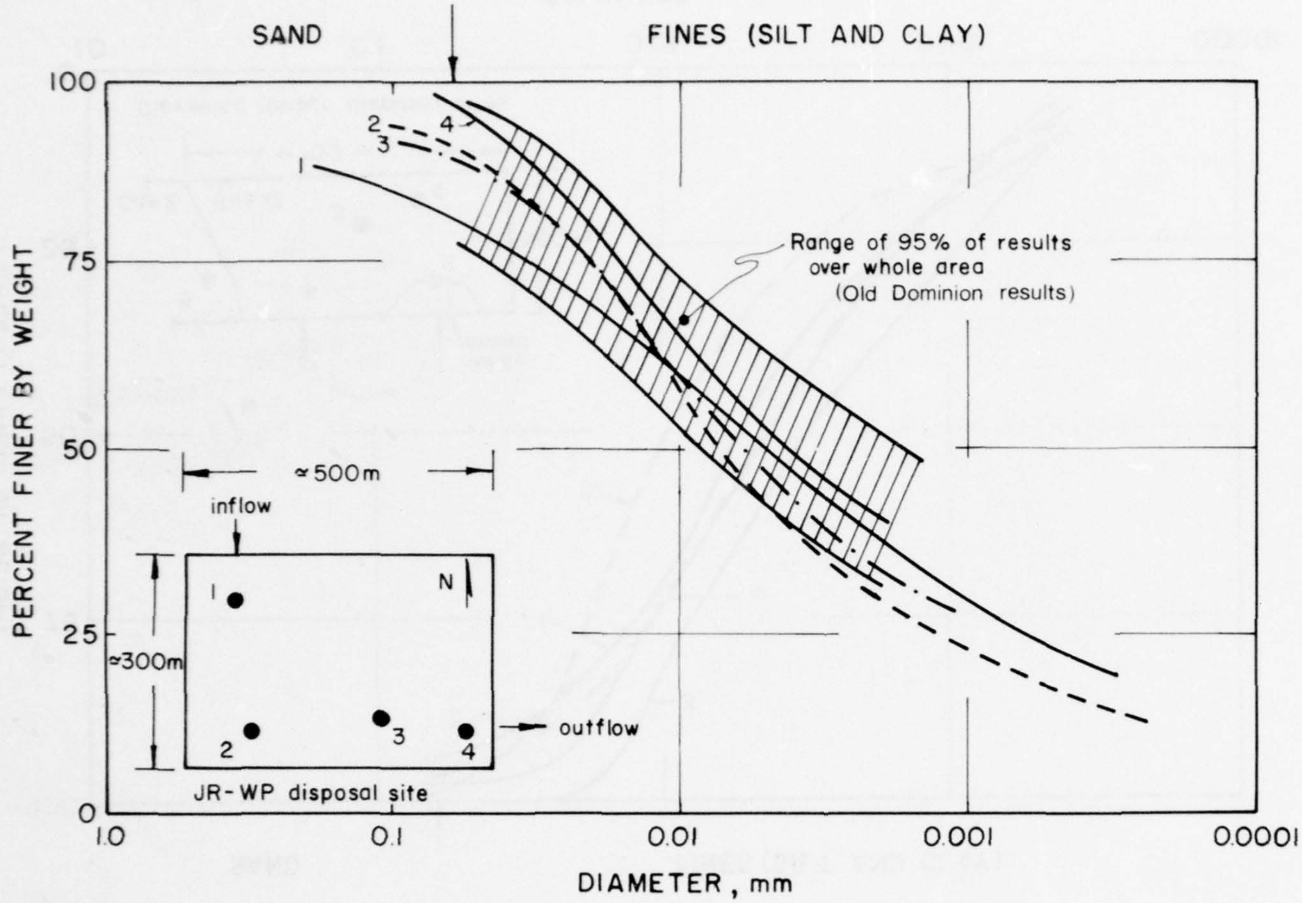


FIGURE 12. SPATIAL DISTRIBUTION OF SOLIDS IN JAMES RIVER-WINDMILL POINT SITE

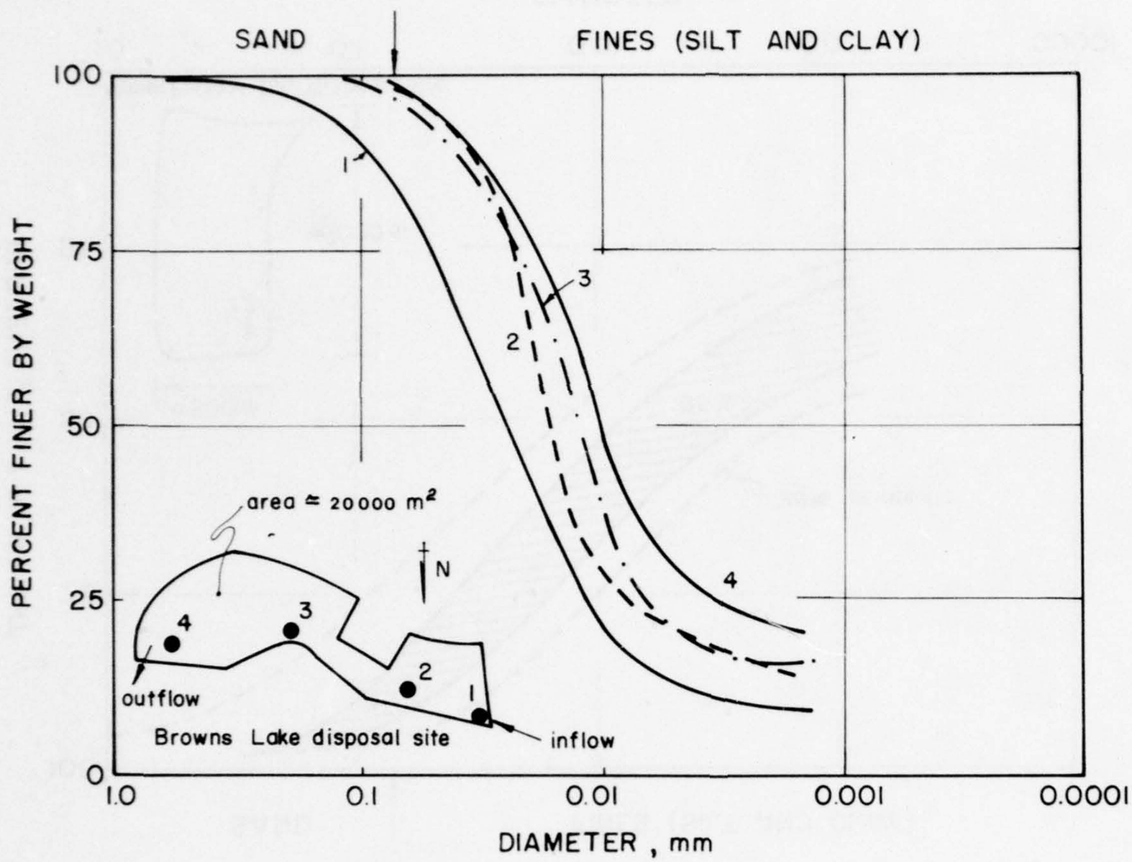


FIGURE 13. SPATIAL DISTRIBUTION OF SOLIDS IN BROWNS LAKE SITE

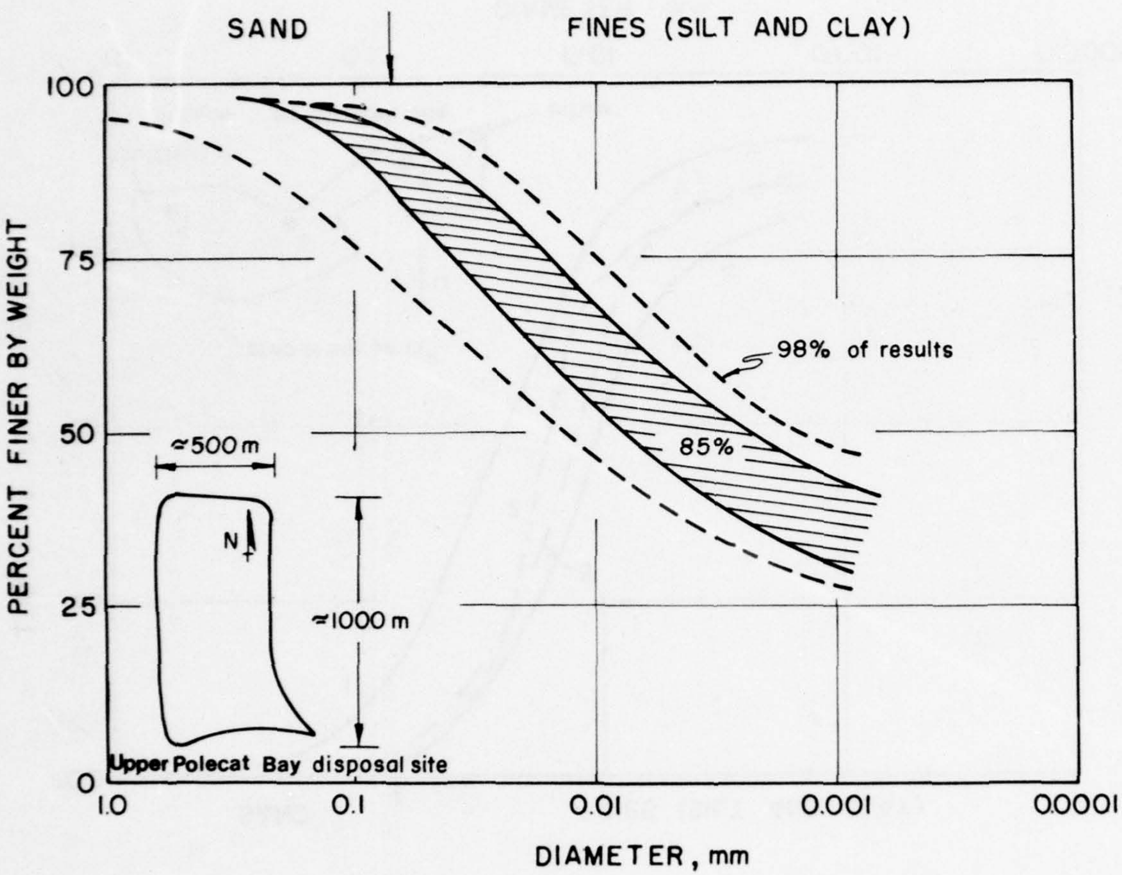


FIGURE 14. SPATIAL DISTRIBUTION OF SOLIDS IN UPPER POLECAT BAY SITE

the pond no. 2 had been recently altered with equipment, which might explain the discrepancy shown by Sample 5.

43. In Branford Harbor, MIT ran a field study of a 10-year-old upland disposal site (see Appendix A) and obtained grain-size profiles both in the horizontal and vertical planes. Figure 8 illustrates the various grain sizes encountered in the horizontal plane as measured on samples at depths between 15 and 30 cm. Figures 9 and 10 present grain-size curves measured at two stations along a vertical profile.

44. In Cleveland Harbor (Figure 11), the material at all locations in area no. 12 (see figure and Appendix A) did not vary appreciably as of December 1975, except at the inflow. For comparison purposes, the grain-size distribution of the dredged material in the neighboring disposal site no. 2 is also shown.

45. In the James River-Windmill Point site, the dredged material exhibited a similar behavior, with the coarser material accumulating at the mouth of the inflow pipe (see Figure 12).

46. The uniform material from Browns Lake (Figure 13) exhibited very little particle segregation. The curves in Figure 13 represent only a few of the several tests run by WES throughout the area; the data shown were obtained from samples recovered at a depth of 1 m. The samples have very similar grain distributions as curves 2, 3, and 4 except those very near the inflow pipe (Curve 1, Figure 13). The uniform silty material becomes finer with increasing distance from the inflow pipe.

47. Finally in the Upper Polecat Bay disposal site, WES conducted another series of tests, but observed very little scatter, as shown in Figure 14. Samples were taken over the entire 3-m depth of dredged material.

48. In conclusion, the last 8 figures show that:

a. Very little particle segregation occurred in the disposal sites under study.

b. The zone of influence of the inflow pipe, where a fan-shaped accumulation of coarser particles occurs, is of limited extent. For the cases under study, the extent of this zone of influence seems less than a 200-meter radius from the inflow pipe.

c. For large areas ($\geq$ 25,000 m^2) particle segregation can be considered minor.

Total Unit Weight of Dredged Material

49. Application of the methodology requires knowledge of the total unit weight of dredged material. This section summarizes measurements of this property for various dredged materials. Given the degree of saturation, the total unit weight, γ_t, can be backfigured from the void ratio of the dredged material. On the other hand, γ_t measured in the field and the laboratory enables one to check the predicted void ratio.

50. Table 5 presents total unit weight determined on three types of dredged materials, Branford Harbor, Upper Polecat Bay, and Delaware River. Measurements were made at various depths between 0 and 10 m, both on newly deposited material

Table 5
Total Unit Weights Measured on Dredged Material

Disposal Site	Total Unit Weight, g/cc	Comments	Source of Information
Branford Harbor	1.43	-Block samples -1 m below crust -10 yrs after disposal	MIT
Upper Polecat Bay	1.47	-2 m below crust -shortly after disposal	WES
Delaware River	1.54 (1.5-1.6)	-4 sites -2 to 10 m depths -New sites and 50-yr old site	Ref. 7

Table 6
Conductance and pH of Supernatant Fluid

Disposal Site	Conditions	Relative Conductance*	pH
Cleveland	Field, November 1975	0.33	--
Harbor no. 12	Field, March 1976	0.28	6.5
	Tests no. 3**	0.19	6.25
	4**	0.25	6.25
	5**	0.25	6.25
Browns Lake	Field, April 1976	0.25	7.25
	Test no.1**	0.15	7.0

*Ratio of conductance of sample to conductance of 2% Normal KCl solution
**Laboratory column sedimentation test at MIT

and in areas 50 years old (γ_t = 1.43 to 1.58 g/cc for all specimens). In all cases, measurements in the drying crust were neglected; the section on measurements of field void ratio of dredged material will indicate total unit weight values on this order. In the case of the Delaware River material (from 4 disposal sites in either Pennsylvania, Delaware, or New Jersey), Figure 15 presents average grain-size distributions at each site. Although the materials differed slightly, γ_t measurements showed very little scatter, and the grain-size distributions compared very well with the range of grain sizes under study (see Figure 3).

Rate of Settling of Dredged Material

51. This property is related to the type of solids in suspension, the solids concentration, and the ambient water conditions. Measurements were made on materials from Branford Harbor, Cleveland Harbor, James River, and Browns Lake. MIT[3] described the procedure for measuring the rate of settling in the laboratory from stillwater column sedimentation tests and discussed the hypotheses and assumptions inherent to this approach. To reproduce field salinity conditions in the laboratory, field water conductance and pH measurements were taken and compared with the properties of the water used in the laboratory tests. Table 6 summarizes these data on two materials. Consecutive tests on the same material using water decanted in the previous test verified the repeatability of the procedure.

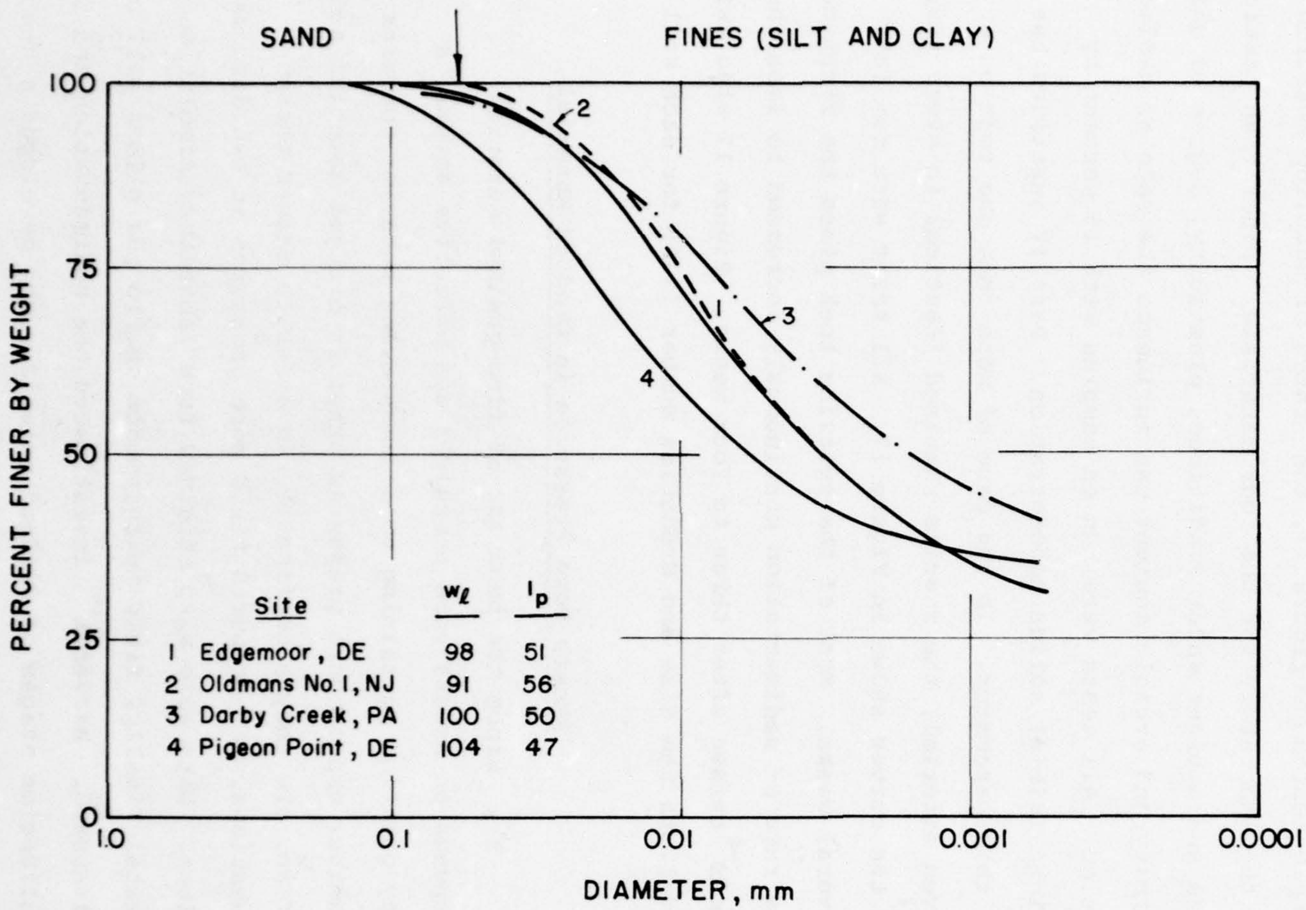


FIGURE 15. GRAIN-SIZE DISTRIBUTION OF DREDGED MATERIAL IN DELAWARE RIVER DISPOSAL SITES

52. Figure 16 plots the grain-size distributions of each sample tested and Figure 17, the rates of settling measured in the laboratory for the four materials. Other than particle size and ambient water conditions, plasticity, degree of uniformity, and organic content can influence the rate of sedimentation. All tests were run on samples with 15 percent by weight initial solids concentration. Part IV justifies use of this parameter. In the case of more than one test on a given material, the results remained identical in every respect to the curves shown in Figure 17. All tests were run for several weeks. *Most of the settling took place the first day;* the rate of sedimentation continuously decreased to less than 1×10^{-4} cm/sec after three to four weeks. Figure 17 also defines and lists the Size and Gradation Number (SGN) for each soil tested.

Excess Pore Pressures in Dredged Material

53. Since the behavior of fine-grained material depends on excess pore pressures and effective stress, a key question pertaining to sedimentation behavior concerns whether excess pore pressures exist in dredged material and if so, are they significant? In order to answer these questions, MIT measured field pore pressures at two disposal sites. Data were also obtained from laboratory simulation tests. Finally, field measurements on Florida slimes will be discussed. Barvenik[14] investigated the sedimentation and consolidation stages of dredged materials and developed a new pore pressure-sedimentation cell to measure excess pore

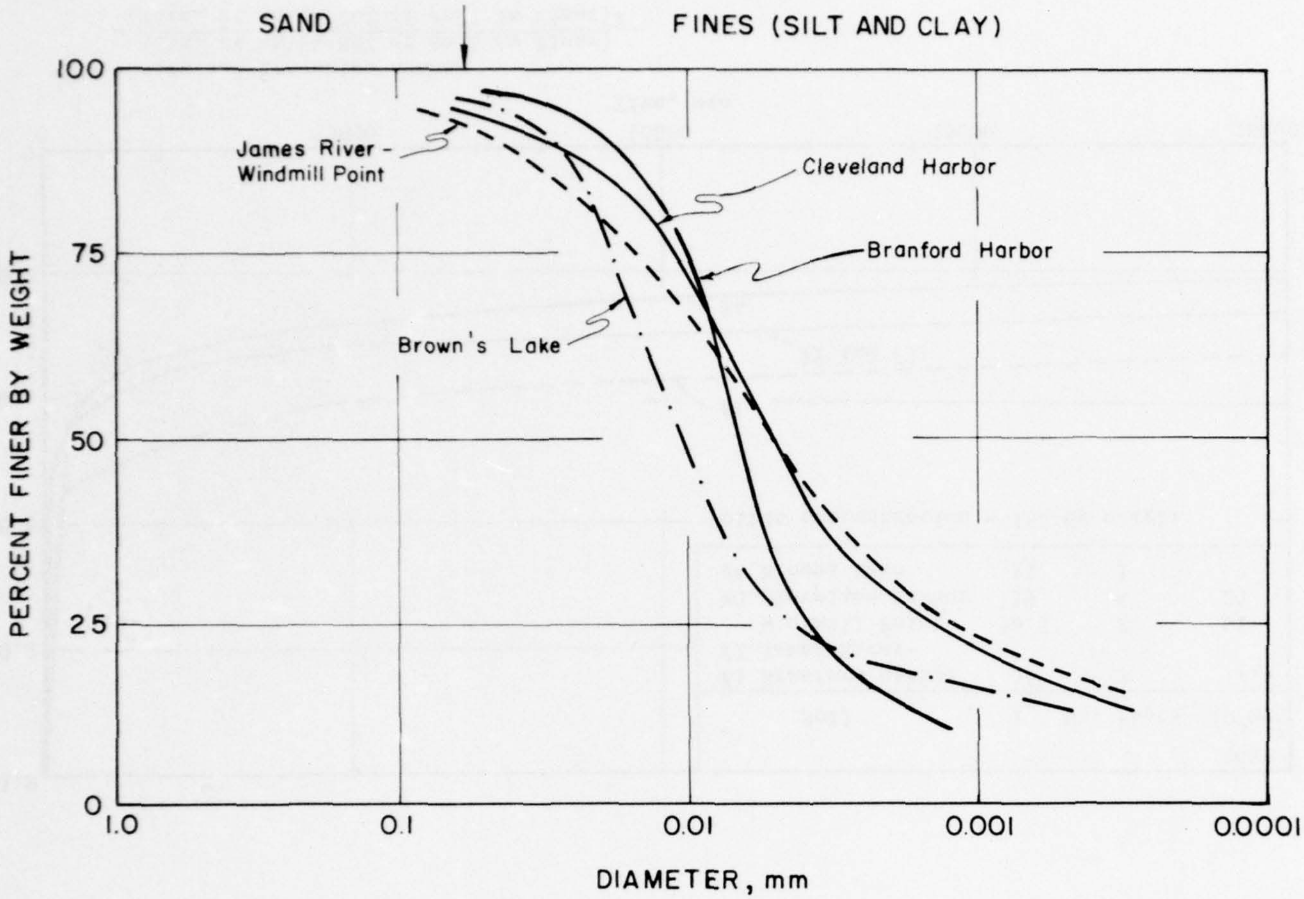
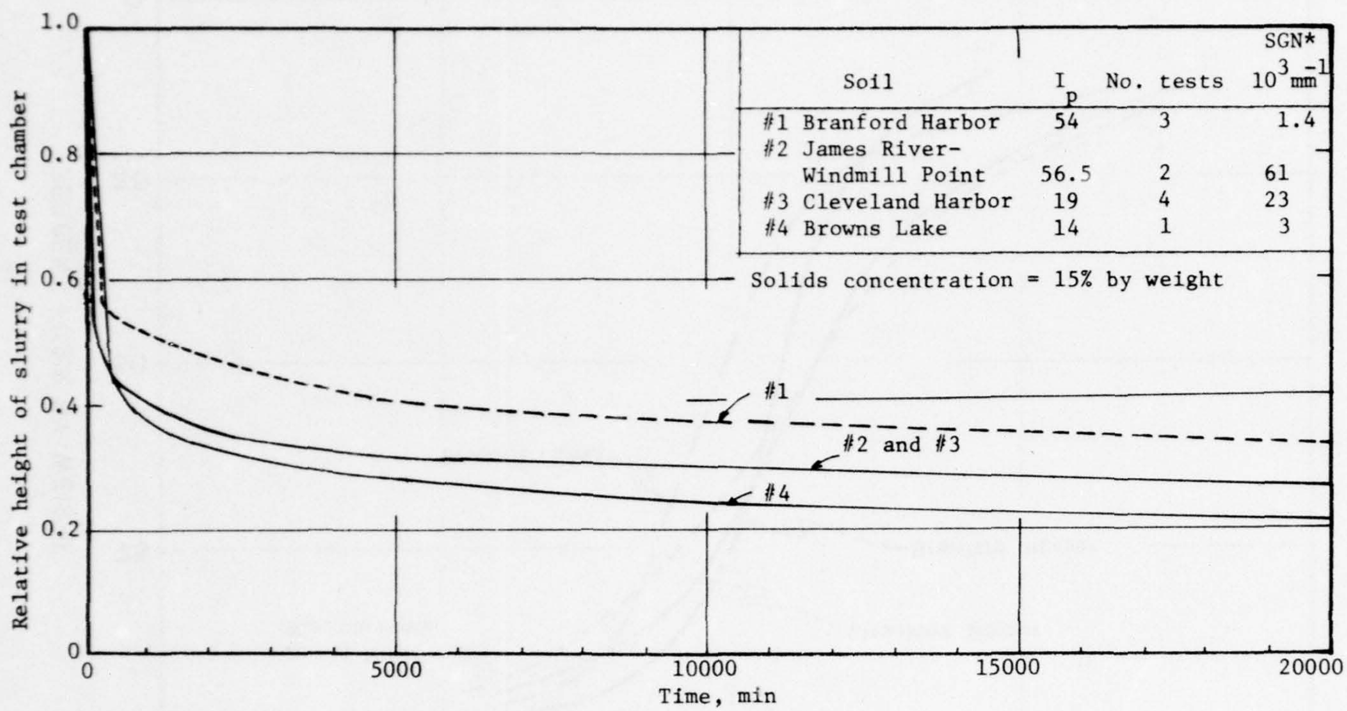


FIGURE 16. GRAIN-SIZE DISTRIBUTION OF SAMPLES USED IN SEDIMENTATION TESTS



*SGN = size and gradation number

$$= \frac{\text{(dia. at which 85\% of soil is finer)}}{\text{(dia. at which 20\% of soil is finer)}^2}$$

Figure 17. Settling rate of dredged material

pressures in the laboratory.

54. Figure 18 summarizes the evolution of excess pore pressures with time and the solids concentration observed after 8 months of self-weight consolidation. The excess pore pressures in Cleveland Harbor material were dissipated after 5 months.

Cleveland Harbor

55. In March 1976, three months after completion of the 1975 dredging operation and two weeks prior to the start of the 1976 operation, MIT measured excess pore pressures at three stations in Cleveland Harbor disposal site no. 12 (see location plan in Appendix A). The site located in Lake Erie was covered by approximately 5 m of water except at Station No. 2, where a mound of 1 to 2 m of sandy dredged material was exposed (Figure 11). Measurements were taken with the pore pressure probe developed by Wissa et al.[15] A high air entry porous stone at the tip allowed measurement of pore pressure, even in the event of gas formation in the material.

56. Figure 19 presents the results of the investigation at the three stations. Practically no excess pore pressures were measured at a depth of 3 m at Station 2, but this was to be expected in sandy material. However, a linear increase of excess pore pressures with depth was obtained in the fine-grained material at Stations 3 and 4. Figure 19b also describes the profiles at Stations 3 and 4, based on Corps of Engineers' (Buffalo District office) soundings. The dredged material elevation and thickness differed at each station,

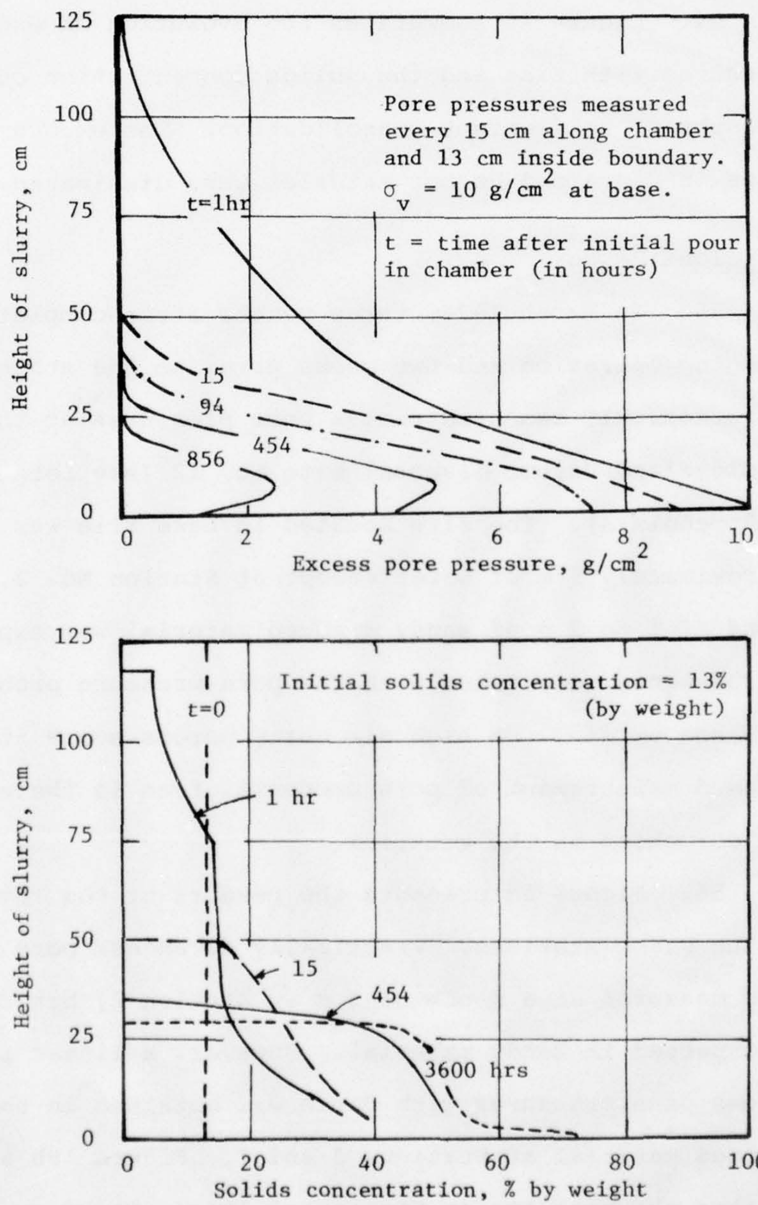


Figure 18. Excess pore pressures and solids concentration in laboratory model

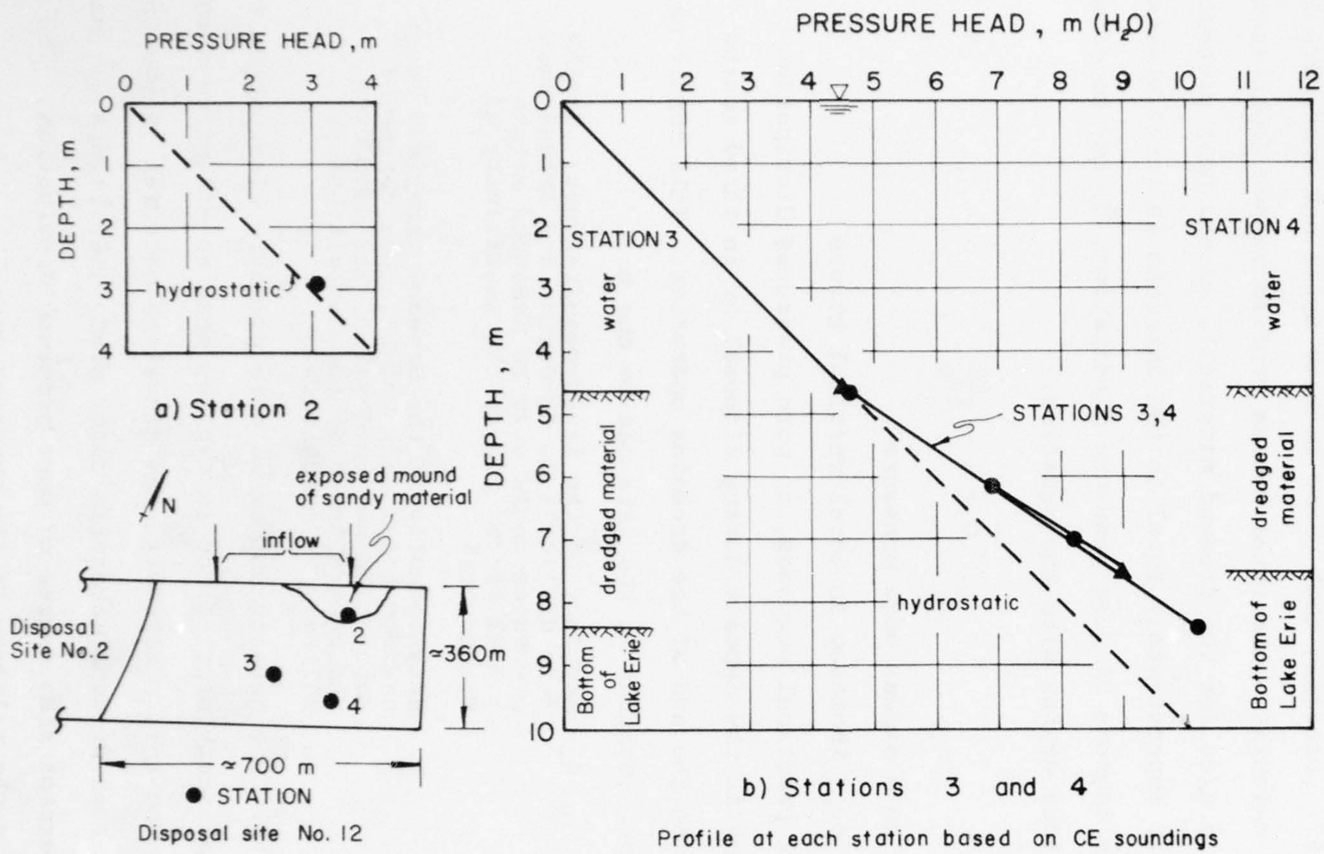


FIGURE 19. EXCESS PORE PRESSURES IN CLEVELAND HARBOR DREDGED MATERIAL

but the excess pore pressure profile remained similar.

57. Dredging took place between April and December, 1975. If one calculates the total stress profile versus depth (using γ_t = 1.5 g/cc for the dredged material), excess pore pressures appeared approximately equal to the increase in total stress. Average degrees of pore pressure dissipation, $\bar{U}$, may be computed at various depths with the equation:

$$\bar{U} = 1 - \frac{\Delta u}{\Delta \sigma_v} \tag{6}$$

where Δu = excess pore pressure

$\Delta \sigma_v$= increase in total vertical stress

For all practical purposes, no pore pressures dissipation occurred in the deposit during disposal or in three months following the end of the dredging operation. This result may be in error. Scatter in the data can be due to:

a. Accuracy of the field measurements: depths were difficult to determine and excess pore pressures could only be measured within $\pm$ 0.02 kg/cm^2 due to the sensitivity of transducer.

b. Heterogeneity of the dredged material: a uniform total unit weight, thus degree of saturation and void ratio, was used over the entire depth of the deposit but is unlikely in practice.

58. The measurement of no pore pressure dissipation is also somewhat surprising, since it implies that no effective stresses act on the soil. Moreover, the Cleveland material is one of the coarser dredged materials under study (see Figure 3); one would expect some degree of pore pressure dissipation. The authors question the validity of the measured data.

Branford Harbor

59. The authors measured pore pressures in March 1976 in the Branford upland disposal site, ten years after sediment from Branford Harbor channel was deposited in the site. In this old site covered by 10 to 15 cm of water, the probe penetration was more difficult than in Cleveland Harbor area no. 12, but could be done manually. The dredged material had, however, enough consistency to allow walking (although with difficulty) on the site. Previous investigations done by the Corps of Engineers (New England Division) and by MIT in two test pits, indicated that the area had only 1.7 m of dredged material over the original fibrous peat and clayey silt foundation.

60. Figure 20 presents the results of the measurements at four stations. Excess pore pressures appear only in the foundation in the middle of the area. However, measured excess pore pressures were so small that complete dissipation occurred before ten years. Scatter in the data shown may have come from two sources:

- a. Uncertainty in the water table elevation.
- b. Sensitivity of transducer used: the measurements were really too small for the range of stress of the transducer used (0-7 kg/cm^2 for the first pore pressure probe, 0-14 kg/cm^2 for the second probe).

The fact that pore pressures in the dredged material were entirely dissipated after ten years is reasonable since the thickness of the deposit was very small.

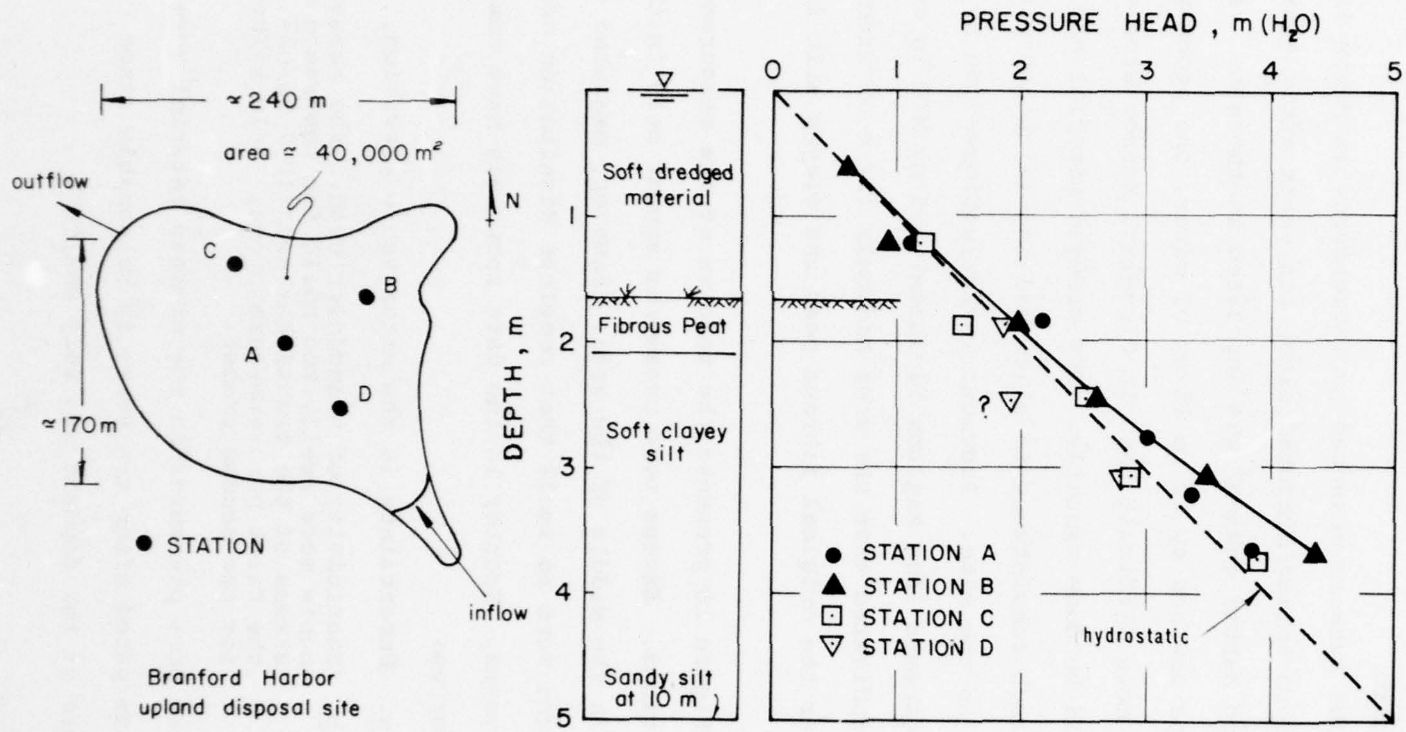


FIGURE 20. EXCESS PORE PRESSURES IN BRANFORD HARBOR DREDGED MATERIAL AND UNDERLYING FOUNDATION 10 YEARS AFTER DEPOSITION

Experience with Florida slimes and Japanese model clay

61. In Florida slimes (nonhomogeneous slurry material at 8 percent by weight initial solids concentration, with w_l = 125-275 and I_p = 75-175),[16] excess pore pressures measured in the field also took a long time to dissipate. (Personal Communication, 15 April 1977, R.T. Martin, Senior Research Associate, MIT). For example, in a 6.5-m-thick slime deposit, pore pressures were still near the total stress six months after deposition. Ladd[16] modelled the consolidation of these slimes using the Olson finite difference sand-drain program.[17] Results of his analyses shown in Table 7 indicate the effects of thickness of deposit and drainage conditions. All cases started off from a "sedimented" state with a very low initial effective stress. For deposits thicker than two m, the time for 90 percent consolidation becomes very important.

62. The simulation analyses shown in Table 7 used a coefficient of consolidation, c_v, of 2×10^{-4} cm^2/sec. Table 8 compares c_v values for each dredged material under study, as obtained from DM-7 correlations between coefficients of consolidation and liquid limit.[18] Values listed apply to completely remolded or normally consolidated states. Also shown are measured c_v's on two materials during the 1975 MIT marsh creation research.[3] The measured data indicate that use of DM-7 values is questionable since c_v varied importantly with stress level in the laboratory.

63. In Japan, a model clay was allowed to settle in a laboratory test box 150 cm x 100 cm x 100 cm.[19] With single drainage,

Table 7

Parametric Consolidation Analyses on Florida Slimes

Thickness of Deposit m	Single Drainage			Double Drainage		
	ρ_f m	t_{50} days	t_{90} days	ρ_f m	t_{50} days	t_{90} days
1.22	0.38	120	500	0.38	40	160
2.44	1.08	450	1900	1.08	130	620
4.88	2.68	1500	3000	2.68	350	1400

ρ_f = final settlement
t_{50} = time for 50% consolidation
t_{90} = time for 90% consolidation
Initial effective stress of 0.005 kg/cm^2

Table 8

Coefficients of Consolidation of Dredged Material Under Study

Material	Liquid limit	Coefficient of Consolidation, cm^2/sec		
		Remolded*	Normally consolidated*	Measured**
Cleveland Harbor	46	5.5×10^{-4}	2.0×10^{-4}	---
Branford Harbor	95	1.7×10^{-4}	5.0×10^{-4}	$10^{-5} - 10^{-2}$
James River-Windmill Point	94	1.1×10^{-4}	2.4×10^{-4}	$10^{-5} - 10^{-3}$
Anacortes	72	1.7×10^{-4}	5.0×10^{-4}	---
Capsante	108	0.8×10^{-4}	2.0×10^{-4}	---
Browns Lake	38	7.5×10^{-4}	2.9×10^{-3}	---
Upper Polecat Bay	90	1.2×10^{-4}	2.8×10^{-4}	---

*From DM-7 (Reference 18)
**From constant head permeability tests, in the 0.0001 to 0.1 kg/cm^2 stress range (Ref. 3).

dissipation of excess pore pressures took more than three months for a 90-cm-thick deposit (see Figure 21). Whereas one may question the value of such a small scale test to represent the behavior in a containment area, the measurements indicate that generation of pore pressures does occur due to self-weight consolidation.

64. Using Terzaghi's one-dimensional consolidation theory for vertical drainage, Johnson[20] studied the effect of thickness of deposit on the time required for consolidation of dredged material and suggested as reasonable coefficient of consolidation the value corresponding to the effective vertical stress at an average degree of consolidation of 70 percent. In his analyses, he chose $c_v = 1 \times 10^{-4}$ cm^2/sec and obtained results consistent with Ladd's[16] (i.e., times were twice as long since c_v was smaller by one-half). For drainage paths greater than one m, more than three years were necessary to achieve 90 percent consolidation. For paths of 3 m, 90 percent consolidation took place over approximately 18 years.

Summary

65. This section points out the following:

a. There is definitively an important generation of excess pore pressures in dredged material under self-weight consolidation.

b. The laboratory model exhibited appreciable dissipation of excess pore pressure with time.

c. Continued field measurements are required to ascertain the sedimentation and self-weight consolidation behavior.

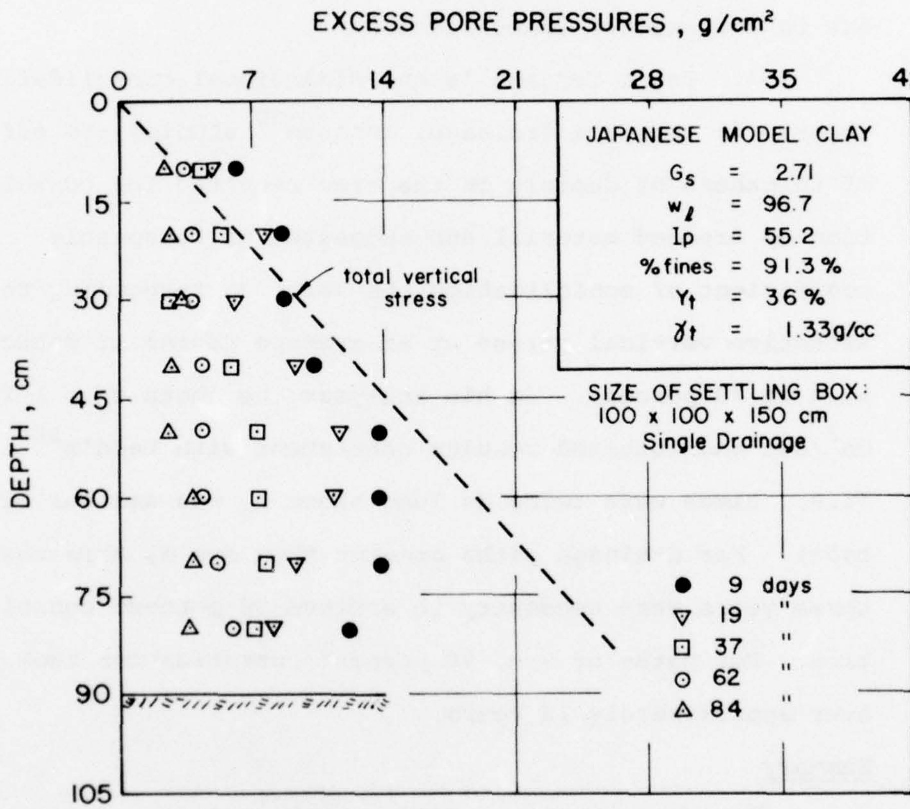


FIGURE 21. EXCESS PORE PRESSURES IN DREDGED MATERIAL (JAPANESE MODEL CLAY)

Void Ratio Versus Depth Distribution of Dredged Material

66. The void ratio of dredged material in a containment area represents one of the most important parameters in the sizing method and can be determined from laboratory tests and/or field measurements. This section presents predicted and measured void ratios versus depth for Branford Harbor, Cleveland Harbor, James River-Windmill Point, and Browns Lake dredged materials and measured void ratios in the Upper Polecat Bay disposal area. The results are then combined with the previous work done by the Philadelphia Long Range Spoil Disposal Study[7] and with field measurements taken at various disposal sites in Japan.

67. Laboratory sedimentation-consolidation tests on dredged slurry at an initial solids concentration of 15 percent by weight enabled prediction of field void ratio distribution of dredged material. Measurements with time of change in elevation of settling suspension, solids concentration versus depth and pore pressures in stillwater sedimentation cylinders (20 and 30 cm in diameter and one to two m high), define void ratio-log effective stress relationships for low stress levels.

68. Figure 17 has shown the rate of settling of four materials under study. Most of the downward movement occurred in the first day. Monitoring continued however

until settling progressed at a rate less than 0.1 cm per day. At this rate, excess pore pressures measured on Cleveland Harbor material indicated dissipation of more than 75 percent of the initial total vertical stress (excess pore pressures due to self-weight consolidation). After completion of sedimentation and self-weight consolidation in the test chamber, water contents, taken approximately in one-cm layers, gave the void ratio versus depth relationship for the material tested. Equation 5 converted water contents in the settling column to void ratios (considering 100 percent saturation). The materials exhibited limited gas generation and a full saturation hypotheses appeared reasonable. Samples cut from the sedimented material were consolidated to higher effective stresses than obtained by self-weight consolidation in a constant rate of strain consolidation apparatus.[21] Data from these tests allowed definition of a continuous void ratio versus log effective stress curve above a vertical stress of 0.1 kg/cm^2.

69. The four materials investigated exhibited nonlinear one-dimensional compression behavior in the laboratory, as shown by the experimental curves in Figure 22. For comparative purposes, the compressibility curve of Route 80 silt (inorganic material from Plymouth, Massachusetts) is also plotted and is proposed as a lower void ratio

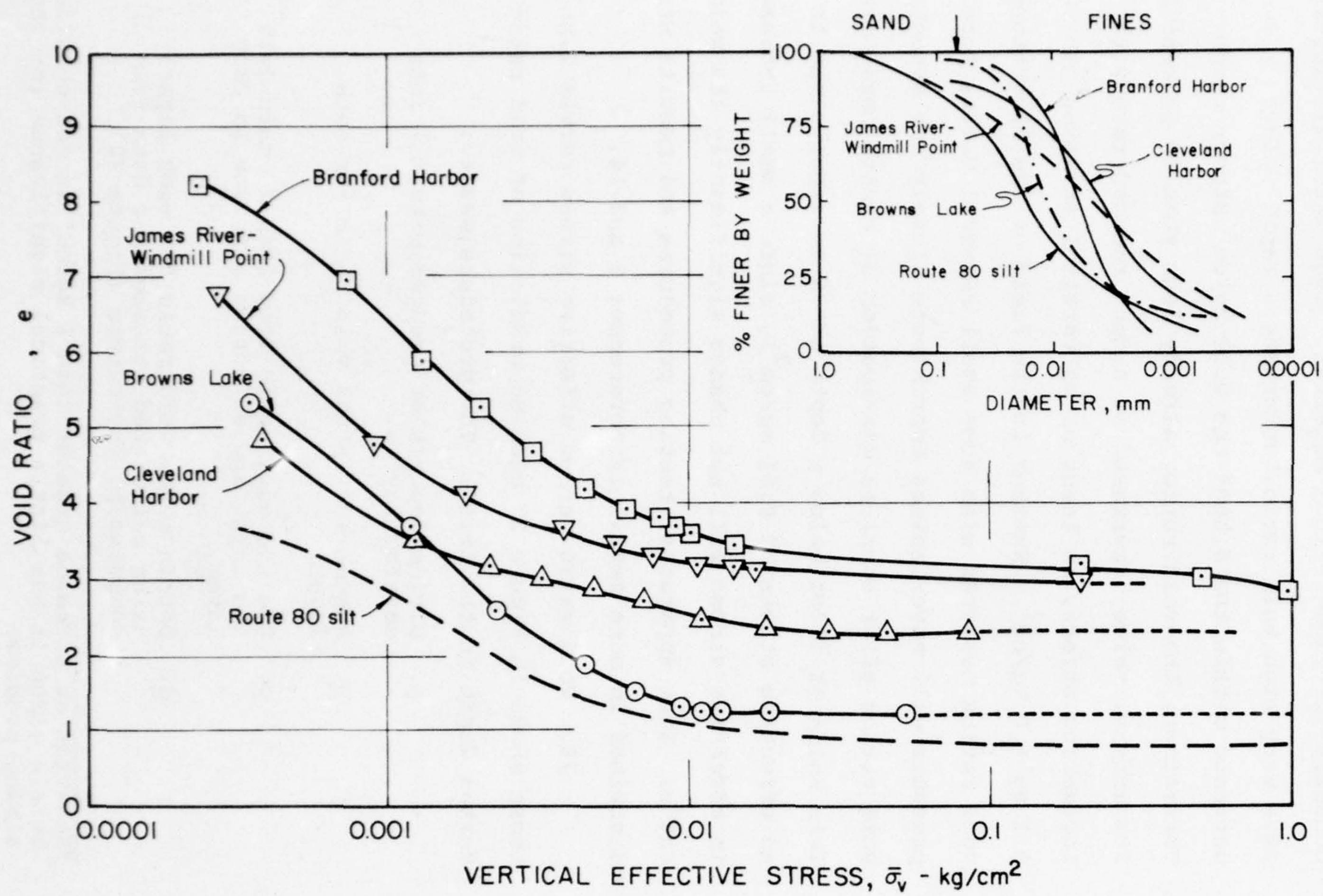


FIGURE 22. ONE-DIMENSIONAL COMPRESSIBILITY OF FOUR DREDGED MATERIALS

boundary for fine-grained material. Each material, initially at a very high void ratio, underwent a rapid volume decrease within the 0.0005 and 0.01 kg/cm^2 stress range. Thereafter, the void ratio, already less than 50 percent of its initial value, decreased at a much reduced rate with increasing stress, at least up to vertical stresses* of 0.1 to 1.0 kg/cm^2. Whether in the field or the laboratory, void ratios measured with some small residual excess pore pressure will nevertheless approximate closely the expected void ratios after complete dissipation of excess pore pressures. This holds at least below a depth of 25 cm (equivalent to an effective stress of 0.01 kg/cm^2), since a small increase in effective stress will not change significantly the void ratio. Test apparatus, testing procedures, and results were described in more detail in references 3 and 14.

70. Void ratio versus effective stress curves like those shown in Figure 22 enabled prediction of void ratio versus depth in the field. The procedure was to:

a. Divide deposit of dredged material into several layers.

b. Assume an average void ratio for each layer.

c. Use the void ratio from Step 2, calculate the total and effective stresses in each layer.

d. Obtain a new void ratio for each layer, using calculated stresses and data from compressibility curves (Figure 22).

*Behavior at stresses greater than 1 kg/cm^2 is not considered herein since it has little practical significance for the sizing problem.

e. Iterate through Steps 3 and 4 until the void ratio versus depth of the deposit remains constant.

71. Plasticity, as well as grain size, affect the void ratio-effective stress relationships of dredged material. Comparison of the plasticity indices with the curves shown in Figure 22 indicates that a high plasticity index implies higher void ratios for given stress levels. Moreover, saltwater Branford Harbor material occupies much more volume in the sedimentation cell than the coarser freshwater Browns Lake material. Based on the compressibility curves shown, the authors predicted the void ratio versus depth distribution of several dredged materials. Figures 23 to 31 present these predictions and compare the results with field measurements, where possible.

Branford Harbor

72. The dredged material profile in the 10-year old Branford Harbor upland disposal site includes approximately 60 cm of fissured clayey silt underlain by 110 cm of soft plastic organic silty clay. Figure 23 compares the void ratio versus depth curve predicted from five column sedimentation tests on channel sediment with the field void ratios computed from natural water contents and total unit weights. Measured and predicted void ratios apply to

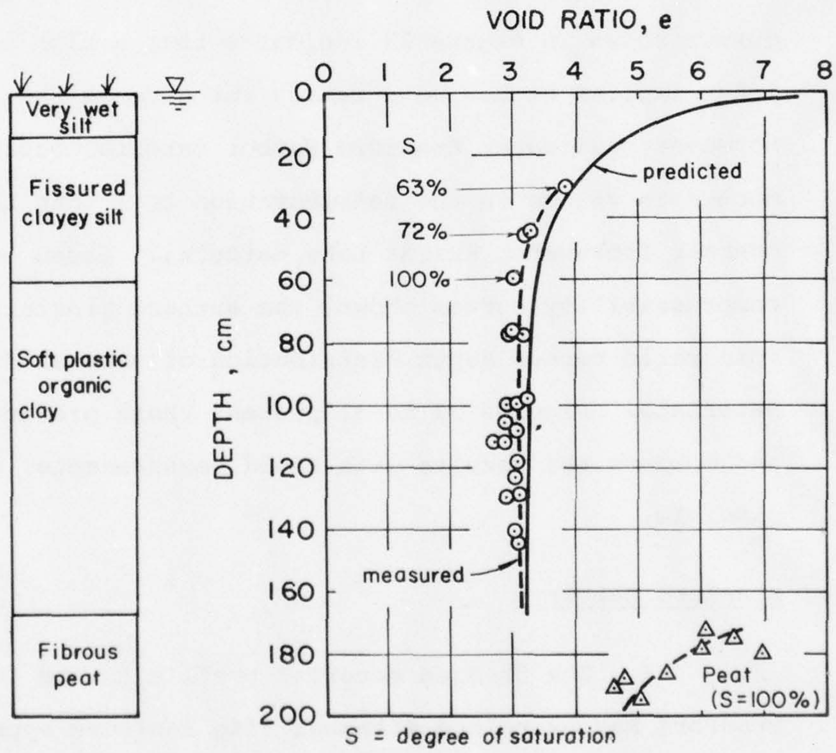


FIGURE 23. PREDICTED AND MEASURED VOID RATIO IN BRANFORD HARBOR UPLAND DISPOSAL SITE

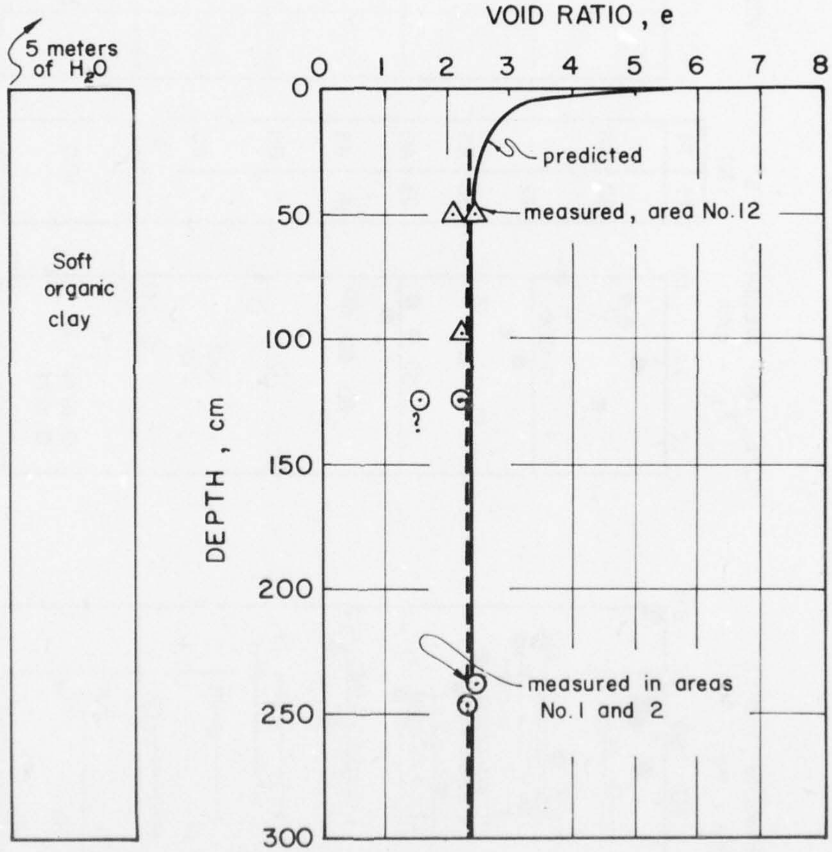


FIGURE 24. PREDICTED AND MEASURED VOID RATIO IN CLEVELAND HARBOR DISPOSAL SITES

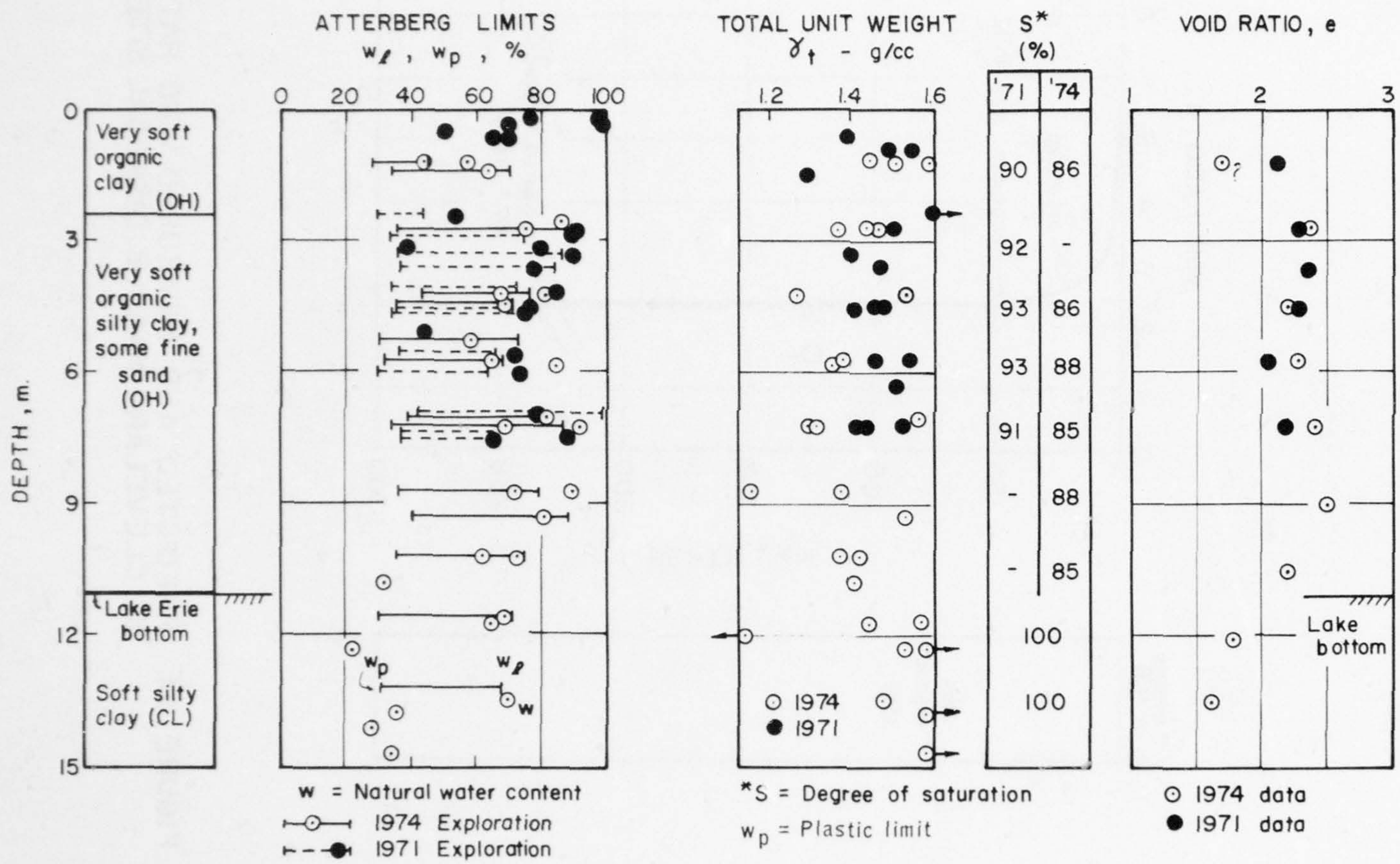


FIGURE 25. PROFILE OF DREDGED MATERIAL AND FOUNDATION IN DISPOSAL AREA NO. I IN CLEVELAND HARBOR

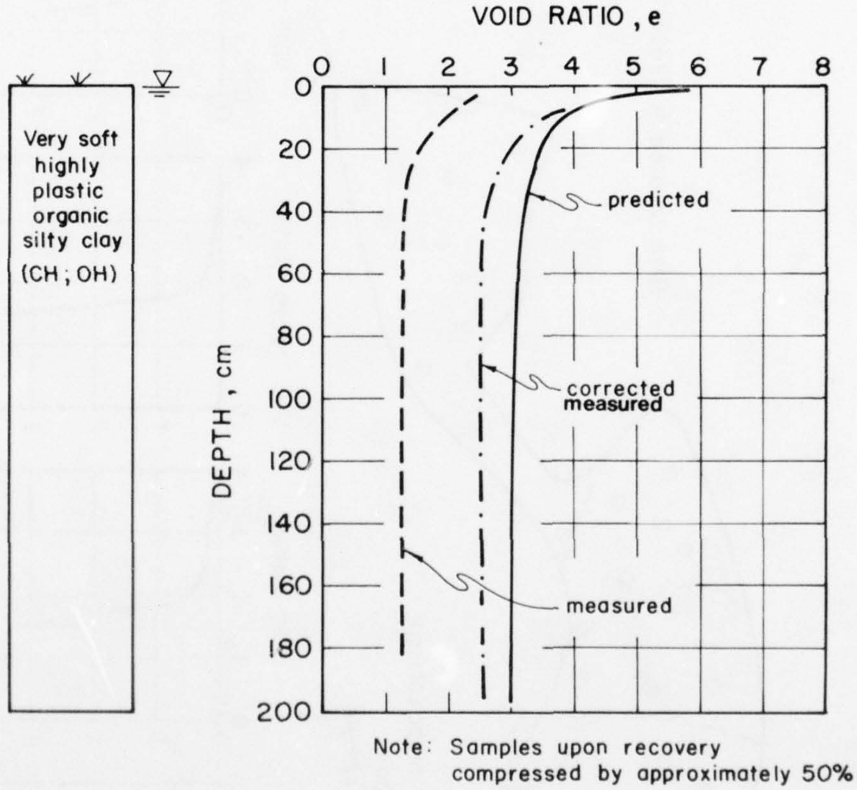
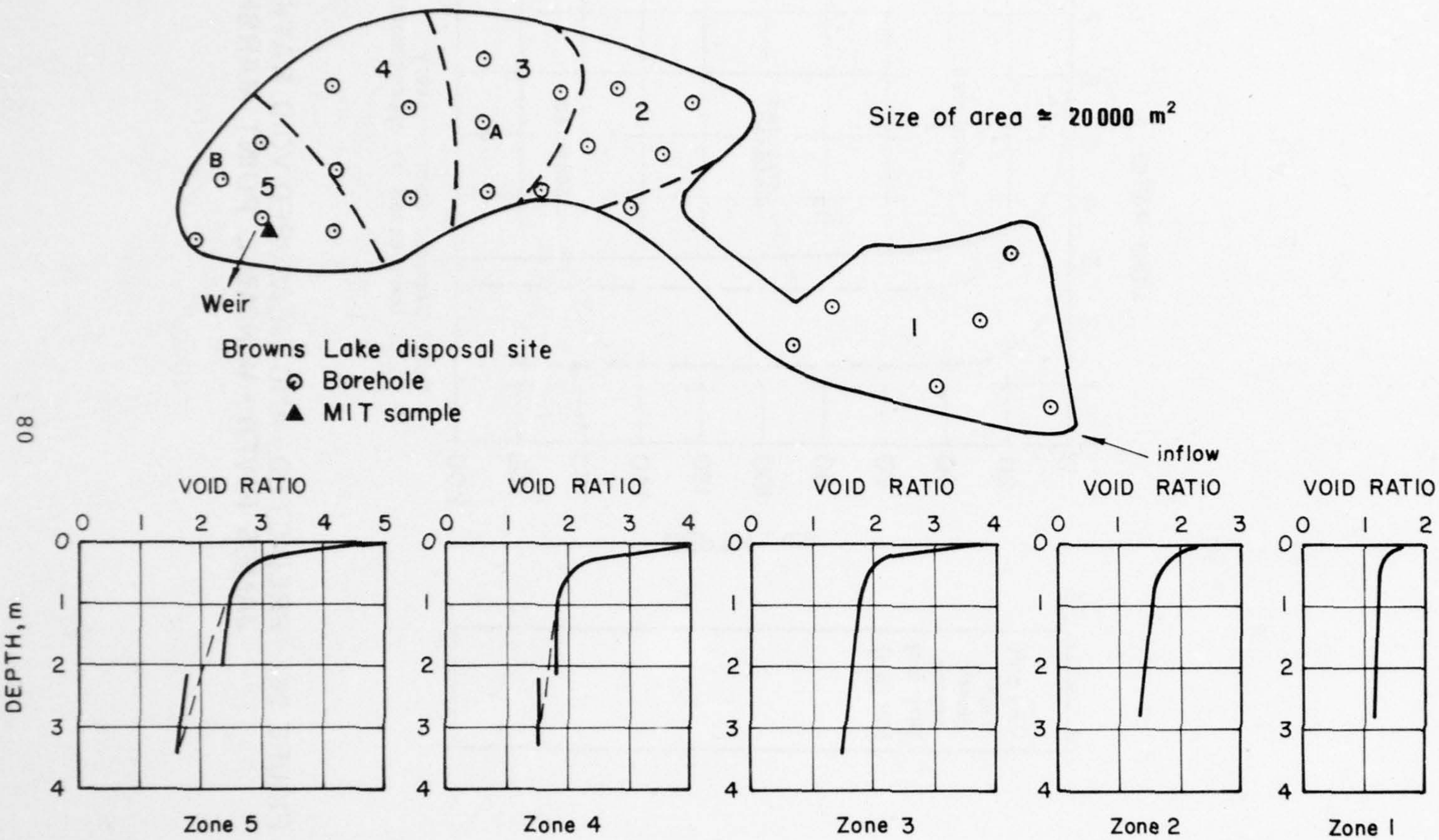


FIGURE 26. PREDICTED AND MEASURED VOID RATIO IN JAMES RIVER - WINDMILL POINT MARSH



Note: see Appendix A for data points

FIGURE 27. MEASURED VOID RATIOS IN BROWNS LAKE DISPOSAL SITE ONE AND ONE-HALF MONTHS AFTER DISPOSAL

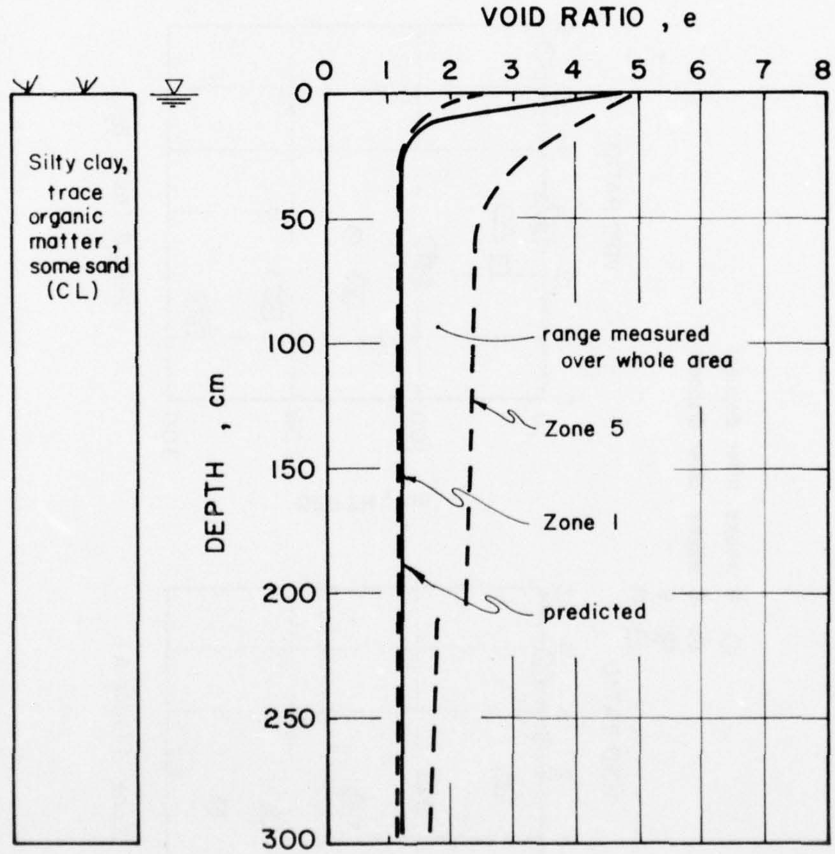


FIGURE 28. PREDICTED AND MEASURED VOID RATIO IN BROWNS LAKE DISPOSAL SITE

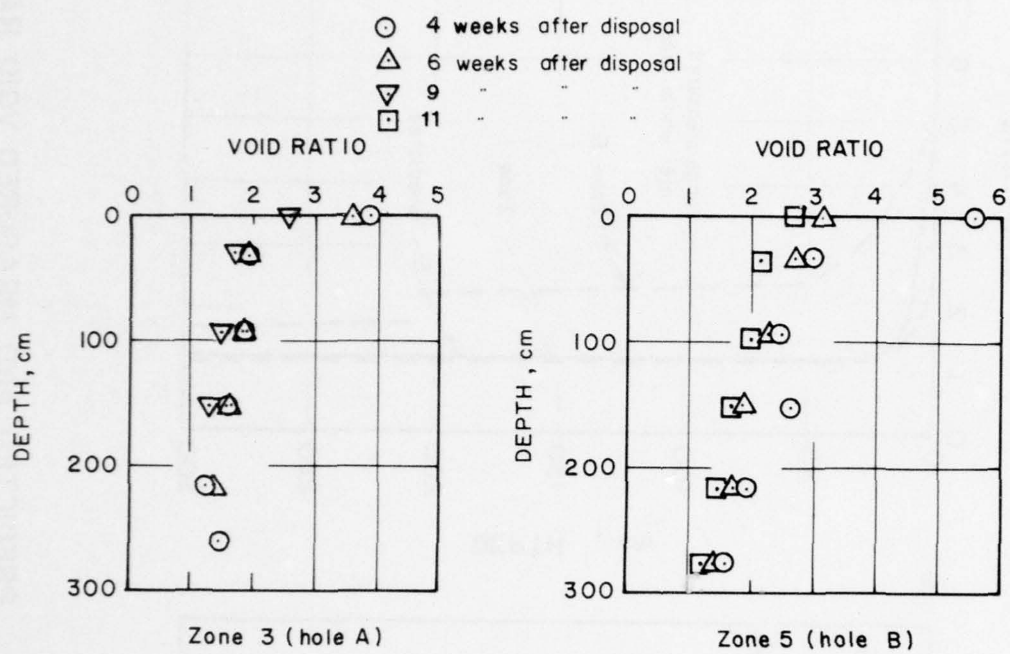


FIGURE 29. EFFECT OF TIME ON VOID RATIO IN BROWNS LAKE DISPOSAL SITE

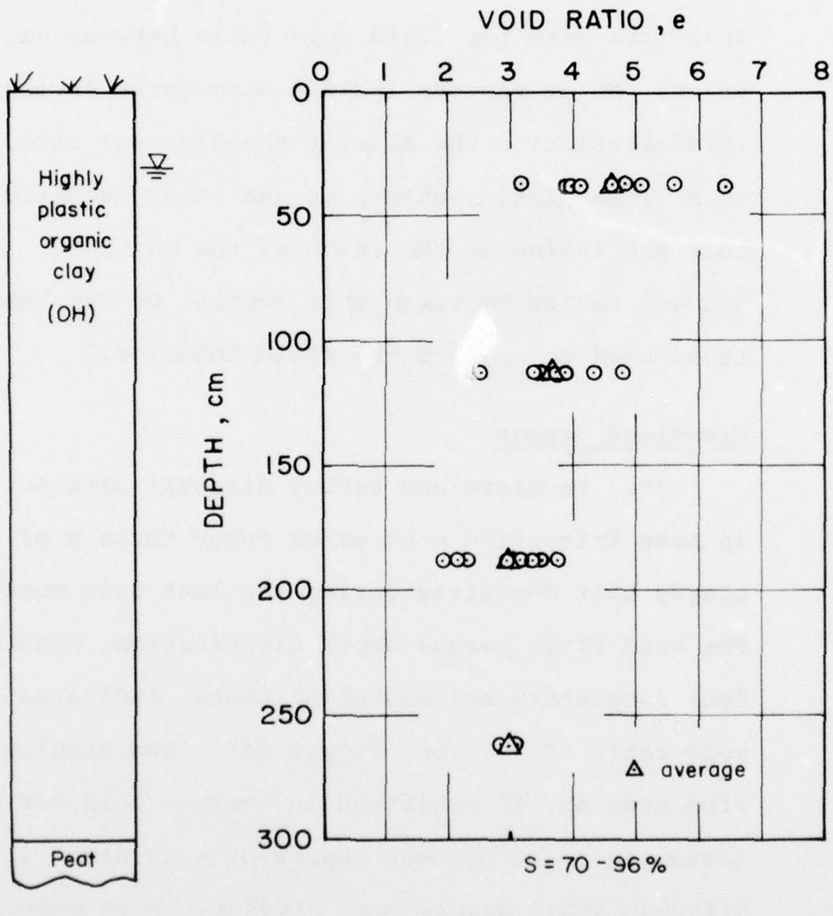


Figure 30. Measured void ratio in
Upper Polecat Bay disposal site

conditions of complete dissipation of excess pore pressures due to self-weight consolidation. They both averaged 3.10 in the softer silty clay. Some uncertainties associate with the field void ratio between depths 0 and 60 cm. Major factors include successive drying and/or rainfalls during the life of the disposal site, periodic tidal immersion, weathering, and other uncontrollable events that can influence the state of the material. All of these can not really be taken into account by the laboratory tests used to predict the field behavior.

Cleveland Harbor

73. In Cleveland Harbor disposal site no. 12, located in Lake Erie, five m of water cover three m of soft organic clayey silt deposited during the last four months of 1975. The void ratio versus depth distribution, predicted from four laboratory sedimentation tests, indicated an average void ratio of 2.3 (see Figure 24). Two samples recovered from area no. 12 exhibited an average void ratio of 2.3 (assuming a 100 percent degree of saturation in the material). Although small excess pore pressures were measured at the site, this value should be representative of the void ratio after self-weight consolidation: if the existing effective stress of the dredged material was on the order of 0.02 kg/cm^2, dissipation of the measured excess pore pressures would increase the effective stress by almost 0.15 kg/cm^2 at the bottom of the dredged material deposit.

Figure 22 shows that the void ratio does not change significantly in this stress range.

74. In area no. 1 in Cleveland Harbor (see Appendix A), void ratios were measured in 1971 and 1974 by the Buffalo District. Figure 25 summarizes the geotechnical profile and index properties measured on samples from these two programs. Although the material in this location differed slightly from the material in disposal site no. 12 (see plasticity chart and grain sizes in Figures 2 and 3), an average void ratio of 2.3, five years after disposal was also measured. Below a depth of one m, the void ratio in the dredged material remained very uniform. Figure 25 shows that void ratios did not change appreciably between 1971 and 1974. This implies that sedimentation and self-weight consolidation were complete by 1971.

James River-Windmill Point

75. In this marsh of very soft organic plastic silty clay (see description in Appendix A), laboratory tests predicted void ratios of 3.0 below a depth of 80 cm, as shown in Figure 26. However, one year after disposal, Old Dominion University measured a void ratio of 1.30 in 21 sampling holes. All specimens were submerged under water when sampled, and the saturation should have been

near 100 percent (Personal Communication, 15 Nov. 1975, D. A. Darby, Professor of Civil Engineering, Old Dominion University, Norfolk, Virginia). During recovery, the samples underwent a volumetric compression of 50 percent. Using 100 percent saturation, the authors corrected measured water contents to account for the volume change. This led to an estimated void ratio between 2.3 and 2.6. The predicted void ratio averaged 3.0 below a depth of 60 cm. The corrected void ratio remains highly hypothetical, but it is difficult to believe that a material as plastic (I_p = 56) and as fine as James River-Windmill Point material would rest at a void ratio of 1.30 after sedimentation and self-weight consolidation (based on knowledge gained from other dredged material).

Browns Lake

76. Browns Lake, Mississippi, was dredged in April 1976. Water contents versus depth were measured during the first ten weeks after disposal. The silty material exhibited low plasticity and contained some sand, but little or no organic matter. The nearby disposal area had an unusual flow pattern due to unconventional shape of the site (Figure 27). Moreover, the small size of the area led to some degree of particle segregation from the inflow pipe to the weir.

After study of the measured void ratios of the material in each of the boreholes in Figure 27, the disposal site was divided into five zones; wherein void ratios versus depth curves were virtually the same in all boreholes. In fact, the experimental data were amazingly consistent. From one zone to the next, as distance from the inflow pipe increased, measured void ratios increased also; at the same time, the material also became finer (towards the exit weir). In Zone 1, the average void ratio over the 3-m depth of dredged material was 1.20, the average void ratio gradually increased from 1.40, 1.60, 1.80, to 2.20 from Zone 2 to Zone 5. The break in the void ratio versus depth curves in Zones 4 and 5 may indicate that coarser material had already settled at the bottom of the area, although this behavior, which can be due to spatial and/or depth segregation, has not appeared in laboratory sedimentation tests, except in the bottom 5 cm of the specimen.

77. Figure 28 presents the void ratio predicted for Browns Lake material from laboratory sedimentation-consolidation tests on a specimen recovered near the weir. The predicted behavior plots on the lower limit of the measured range of void ratios (i.e., near the void ratio measured in Zone 1). The predicted void ratio applies to conditions of no excess pore pressures. The discrepancy between the predicted and measured void ratios in Zone 5 may be due to incomplete consolidation in the finer Zone 5 material. Very small excess pore

pressures are expected, however, in Zones 1, 2, and 3 where coarser material was encountered. Indeed, if one plots the individual measurements during the first 10 weeks after disposal, the behavior shown in Figure 29 was consistently observed: in zones 1 to 3, very little change in void ratio appears between 2 and 4 weeks. However, in Zone 5, the void ratio decreased significantly in the 2-week interval between the field measurements. The behavior in hole B (Zone 5) indicated that settling under self-weight was still important.

78. However, it is doubtful that at the end of self-weight consolidation, the average void ratio for the whole area will be as low as the predicted void ratio. It would therefore seem that the prediction method for void ratios in coarser sediments such as Browns Lake material leads to less satisfactory results than in the case of finer materials.

Upper Polecat Bay

79. In the Upper Polecat Bay disposal site, the Corps of Engineers measured void ratios in the 3-m deposit 30 months after completion of the dredging operation but before the start of a densification program. At that time, the water table was located some 30 to 60 cm below the surface. The investigation included 26 boreholes in which water contents versus depth were measured. Unit weights were available in nine holes, and only those were used to define the void ratio profile in Figure 30 (Appendix A indicates the location of these holes). The

degree of saturation varied from 70 to 97 percent in the 300-cm deposit and the total unit weight varied from 1.15 to 1.57 g/cc. The data show considerable scatter that probably originates from: (1) uneven drying of the material over the 30-month period since disposal; (2) sampling and testing difficulties; (3) slope of the surface of the disposal area and therefore varying water table depth; and (4) local variation in material grain size and plasticity. The average void ratio below 150 cm was 3.00. This value seems very reasonable for this type of material (see grain sizes in Figure 14). No laboratory sedimentation-consolidation tests were done on this material.

Delaware River

80. In 1969, the Philadelphia District published a comprehensive "Long Range Spoil Disposal Study"[7] on the Delaware River dredging operations. This document includes detailed geotechnical investigations of dredged materials in four disposal areas: Edgemoor, Delaware; Oldmans no. 1, New Jersey; Darby Creek, Pennsylvania; and Pigeon Point, Delaware. This section summarizes the void ratios measured at each site in 1967. Only data where degrees of saturation could be computed (i.e., where unit weight data were available) have been considered.

81. In the Edgemoor site, dredged material has been deposited since 1911. Figure 31 indicates the dredged material

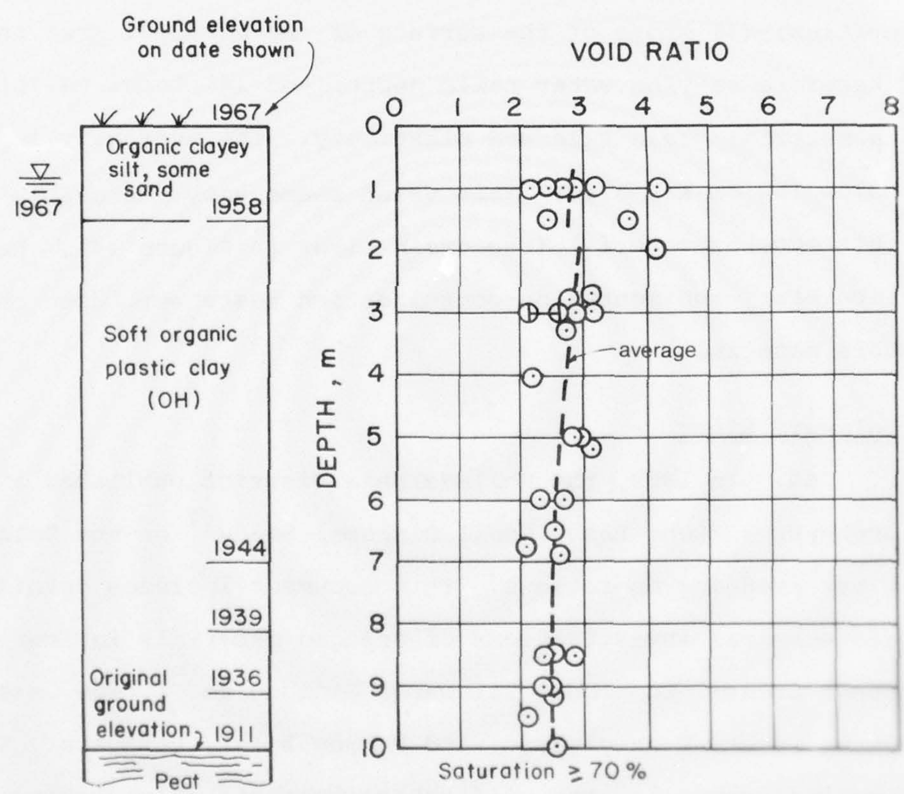


FIGURE 31. VOID RATIO MEASURED IN EDGEMOOR DISPOSAL SITE ON DELAWARE RIVER

AD-A050 038 MASSACHUSETTS INST OF TECH CAMBRIDGE CONSTRUCTED FAC--ETC F/G 13/2
SIZING OF CONTAINMENT AREAS FOR DREDGED MATERIAL.(U)
OCT 77 S M LACASSE, T W LAMBE, W A MARR DACW39-75-C-0074

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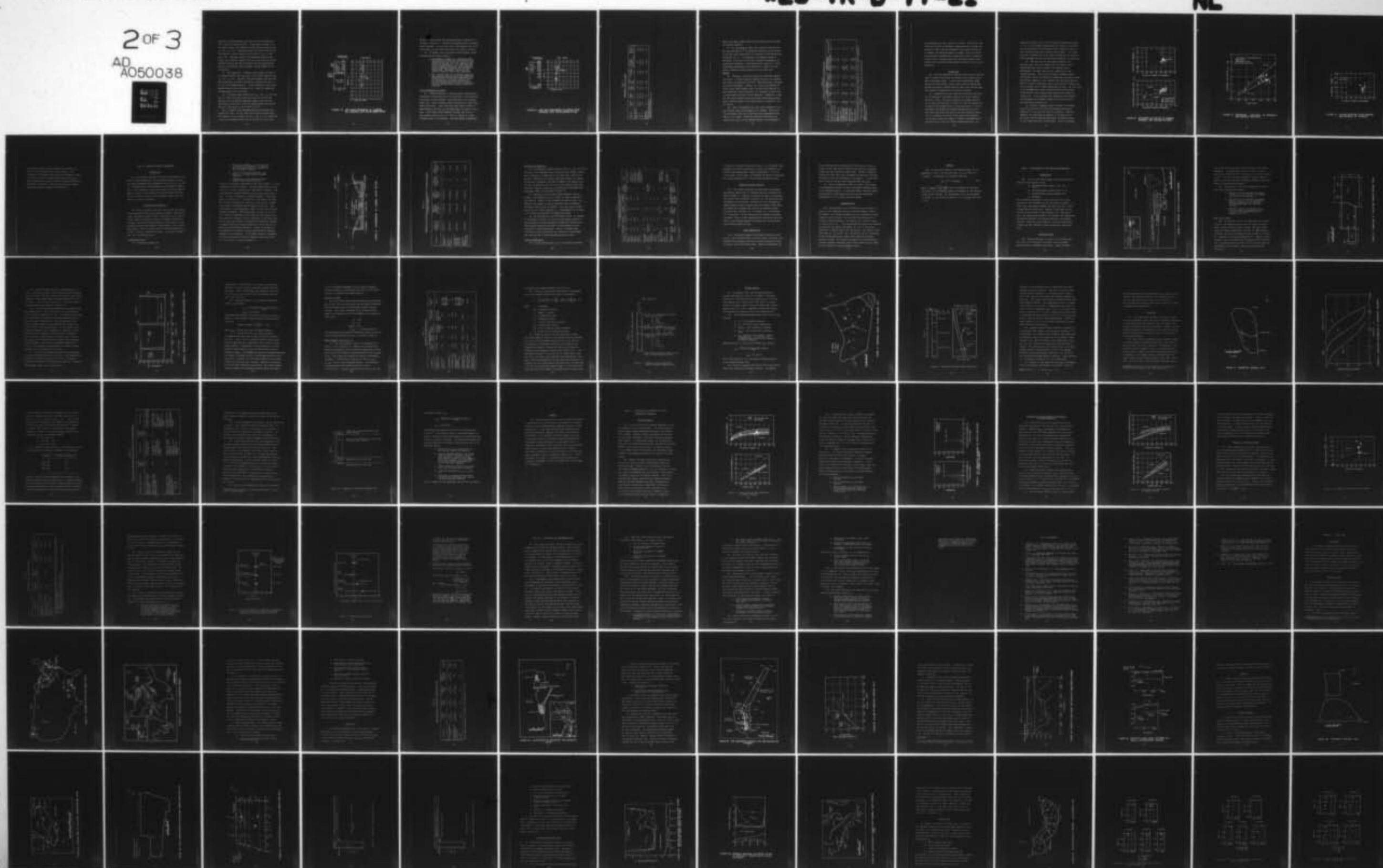

elevation at selected years and the void ratios measured in 1967 in the 10-m thick material. The profile includes 1.5 m of organic clayey silt underlain by soft plastic organic clay (w_l = 98; I_p = 51). Measured average void ratios over the entire depth of plastic organic clay go from 2.9 to 2.5 (see Figure 31). The data, based on 10 boreholes, showed surprisingly little scatter, despite the age of the material and the successive drying periods the deposit must have experienced. Degrees of saturation, when available, varied between 70 and 100 percent.

82. The Oldmans no. 1 disposal site consists of three m of dredged material (OH) overlying a soft organic plastic clay (w_l = 91; I_p = 56). Dredging took place between 1940 and 1962. The limited data available indicated an average void ratio of 2.70 for the dredged material. In the foundation, void ratios seemed slightly lower, averaging 2.50. Figure 32 summarizes the measurements and the profile.

83. The Darby Creek organic clay (w_l = 100, I_p = 50) was also 3 m thick, but only three void ratio data points were available for the material deposited between 1955 and 1966. The degree of saturation in the fill seemed higher than 85 percent with void ratios in the vicinity of 2.60.

84. In Pigeon Point, dredging started in 1948 and continued until 1966. At that time, the 6-m-thick dredged material deposit of soft organic clay (w_l = 104, I_p = 47) exhibited a void ratio decreasing from 2.60 at the top to 2.10 at the

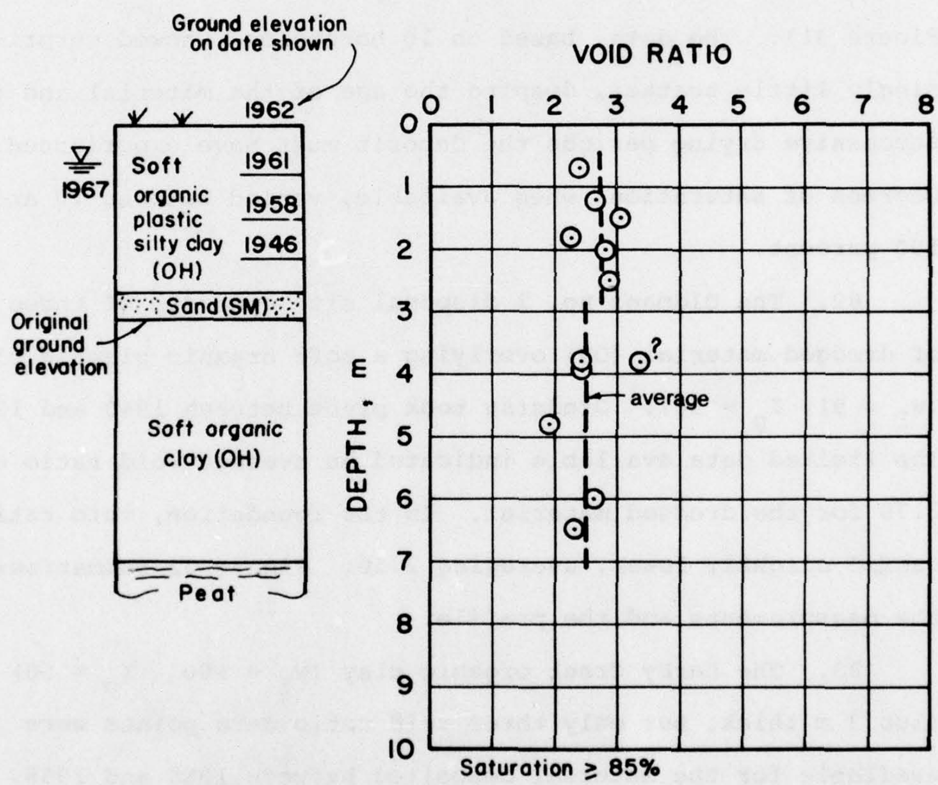

FIGURE 32 VOID RATIO MEASURED IN OLDMANS NO.1 DISPOSAL SITE ON DELAWARE RIVER

bottom. Little scatter was encountered below a depth of 2 m as shown in Figure 33. Degrees of saturation were all greater than 75 percent. In this site, age of the material may not be significant, as void ratio decreased only slowly with depth.

85. In summary, the four Delaware River disposal sites exhibited the following behavior:

- a. The Edgemoor, Oldmans no. 1, and Darby Creek materials, which had very similar grain-size distributions (see Figure 14), and very high plasticity indices ($I_p \geq 50$), showed a void ratio of approximately ≥ 2.60, which remained fairly constant with depth, even though some material had been deposited for more than fifty years. Therefore, the age of the material seemed to have little importance.
- b. The coarser Pigeon Point material deposited more recently than the other three materials exhibited low void ratios in the bottom half of the deposit. Since this disposal site was smaller than the other three,[7] some particle segregation both due to differential settling and horizontal velocity could have occurred.

Field measurements in Japan

86. Although Reference 5 presents several case studies, discussion in this section will be restricted to the materials encountered in Sakai Harbour near Osaka and to the Japanese model clay. Table 9 presents index properties for three Sakai Harbour materials. Grain sizes have been shown in Figure 4. Each material, all with $I_p \geq 50$, comes from a saltwater environment. Four months after disposal, average void ratios in the disposal area were 2.9, 3.1 and 3.3, leading to volume increases from 7 to 30 percent. The data showed considerable

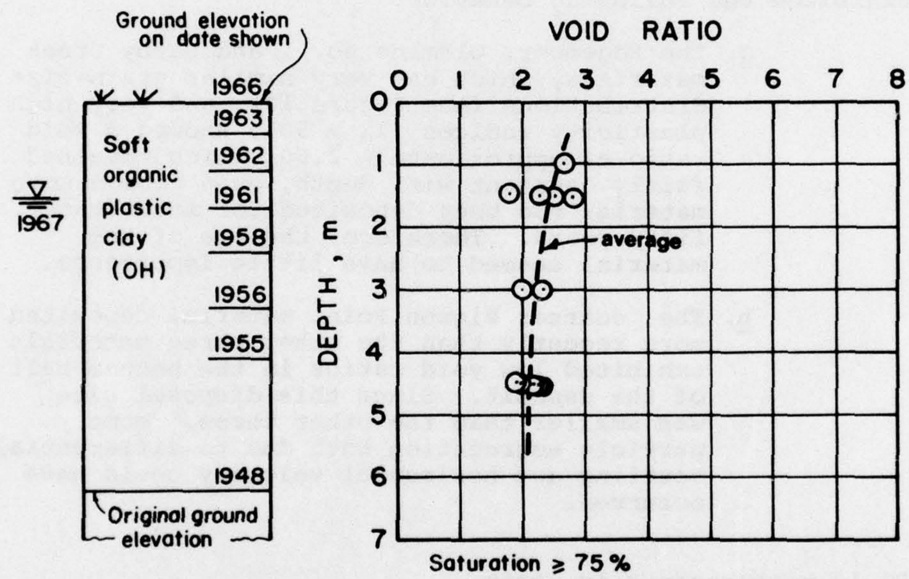

FIGURE 33. VOID RATIO MEASURED IN PIGEON POINT DISPOSAL SITE ON DELAWARE RIVER

Table 9

<u>Measured Void Ratios in Japan*</u>

Material	Liquid Limit	Plastic Limit	Plasticity Index	Liquidity Index	Void Ratio of Sediment, e_o	Void Ratio of Dredged Material, e_{ave}	Specific Gravity of Solids, G_s
Sakai Harbour							
No. 2	75 ± 5	25 ± 5	≃ 50	2.00	2.11	2.9	2.64
No. 3	85 ± 5	25 ± 5	≃ 60	1.43	2.38	2.9-3.4	2.64
No. 4	80	25 ± 5	≃ 55	1.36	2.64	2.9-3.3	2.64
Japanese Model Clay	97	42	55	0.80	2.62	3.3**	2.71

*Saltwater environment

**Predicted from settling box test

scatter and these numbers should be considered only as guides for probable behavior.

87. For the Japanese model clay tested in the settling box mentioned before,[19] the measured void ratio at the bottom of the box, after dissipation of 70 percent of the excess pore pressures, was 3.7. By projecting the expected amount of settlement in the box at the time of complete dissipation of excess pore pressures, an approximate void ratio of 3.3 after self-weight consolidation was obtained at a depth of 80 cm. Table 9 summarizes index properties of the model clay.

Summary

88. Typically, void ratios below one m remained constant with depth. In newly deposited dredged material, the surface void ratio was generally very high. When desiccation occurred, void ratios decreased. However, for storage requirements of a multi-year usage disposal area, the short-term behavior is more important, since desiccation will probably not have time to occur before the next filling operation. Therefore, a typical void ratio profile after self-weight consolidation would have a profile similar to the curves shown in Figures 23, 24, 26, and 28.

89. Table 10 summarizes the void ratios measured in all the disposal areas investigated by the authors. The age of the containment facility at the time field measurements were taken is also shown. Except for saltwater materials, the average void ratios of the dredged material in the disposal

Table 10

Void Ratio of Dredged Material in Disposal Areas

Disposal Site[+]	Channel Sediment Liquid Limit	Channel Sediment Plasticity Index	Channel Sediment Liquidity Index	Channel Sediment Measured Void Ratio	Dredged Material Average Void Ratio Measured	Dredged Material Average Void Ratio Predicted**	Volume Increase[++] %
Branford Harbor*(10)	95	54	0.98	2.50	3.10	3.20	17
Upper Polecat Bay(2)	90	59	----	----	3.00	----	--
James River-Windmill Point(1)	94	56.5	0.75	2.12	2.60	3.00	15
Delaware River							
-Oldmans no. 1(10)	91	56	----	----	2.70	----	--
-Edgemoor(20-50)	98	51	----	----	2.5-2.7	----	--
-Darby Creek(10)	100	50	----	----	2.60	----	--
-Pigeon Point(10)	104	47	----	----	2.1-2.6	----	--
Cleveland Harbor							
-nos. 1 and 2 (4)	73	38	----	----	2.30	----	--
-no. 12 (0)	46	19	1.31	2.05	2.30	2.30	8
Browns Lake (0)	38	14	----	----	1.1-1.5	1.20	--

[+] Index following disposal site indicates age of disposal site in years at time of measurements.

[++] Volume increase $= \frac{1 + e_{ave}}{1 + e_o} - 1.00$, where e_{ave} and e_o are measured values.

*Saltwater environment.

**Below depth of 1 m.

site decrease with lower plasticity indices. Table 9 has also listed void ratios in saltwater dredged material and they are generally larger than the freshwater void ratios in Table 10. In summary, the method proposed to predict field void ratios from laboratory sedimentation-consolidation tests on sediment yielded rather reliable results for the three organic clays studied, but may give less satisfactory results for very silty materials.

Conclusions

90. Particle segregation from the inflow pipe to the weir seems to become significant for disposal area sizing only in small containment areas. In the sites investigated, sandy material settled within a 200-m radius from the inflow pipe. Beyond this sector, dredged material grain sizes did not vary much except in singular locations such as corners.

91. Laboratory settling rates were initially very rapid for all materials (50 percent reduction in slurry height in less than a day). For annual deposits of dredged material on the order of less than 3 m thick, the time for dissipation of excess pore pressures will be relatively short; it can be reasonably stated that self-weight consolidation will be well under way before the start of the next dredging season. In fact, dissipation of most of the excess pore pressures (50 percent) occurs very rapidly. Based on one-dimensional compressibility curves for various dredged materials, the

compression index is very low at effective stresses equivalent to 1 to 5 m of dredged overburden and the change in void ratio during dissipation of the remaining pore pressures as well as that induced by additional loading will be small. For sizing purposes, consideration of the volume occupied by the material after sedimentation and self-weight consolidation is sufficient.

92. The void ratio of the channel sediment, the settling rate, total unit weight, and void ratio of the dredged material can be related to (1) ambient water environment, (2) grain size, and (3) plasticity of the dredged material. Void ratios of channel sediment showed considerable scatter and should be determined preferably through fixed-piston sampling or as a minimum with disturbed sampling. However, Figure 34 indicates higher void ratios for higher plasticity indices and for higher percentage of fines. The void ratio in the disposal area (after sedimentation and self-weight consolidation) also increased with salinity and plasticity (Figure 34). In fact, approximate behavioral relationships for saltwater and freshwater deposits can be deduced from the data shown (see Part VI).

93. Figure 35 compares channel sediment and dredged material void ratios with the relationships proposed by Skempton[22] for sea bed and tidal flat deposits. However, Skempton only described the behavior of inorganic silts and clays, and his generalization does not directly apply to the organic materials investigated. Figure 36 presents

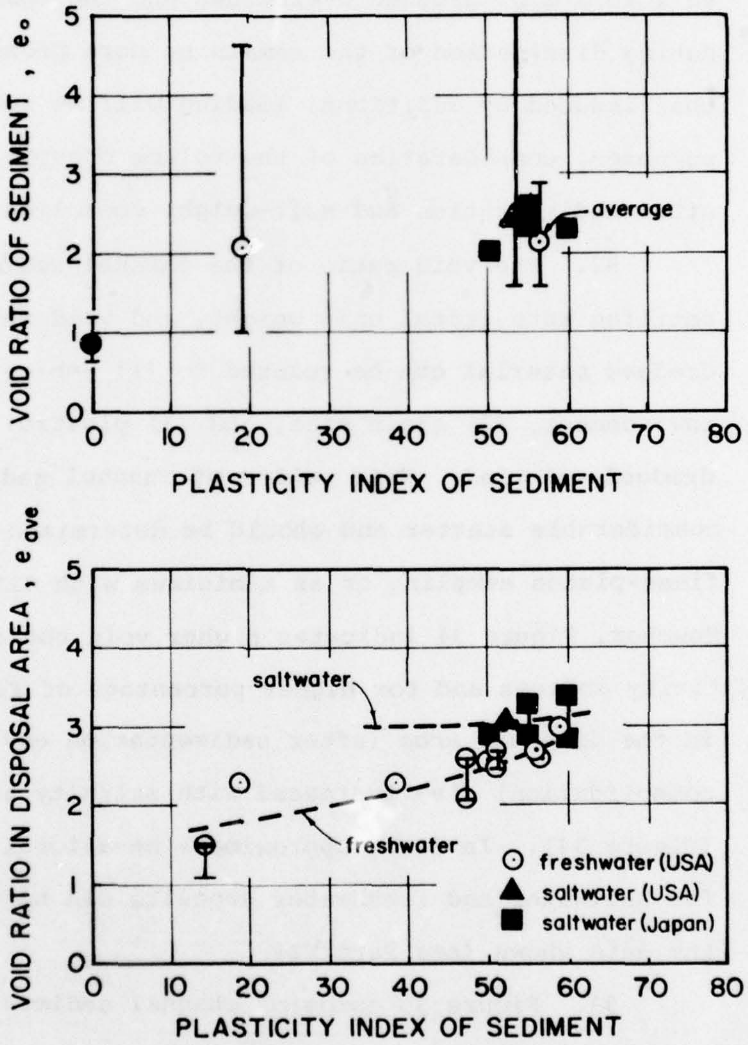

FIGURE 34. MEASURED VOID RATIOS OF CHANNEL SEDIMENT AND DREDGED MATERIAL

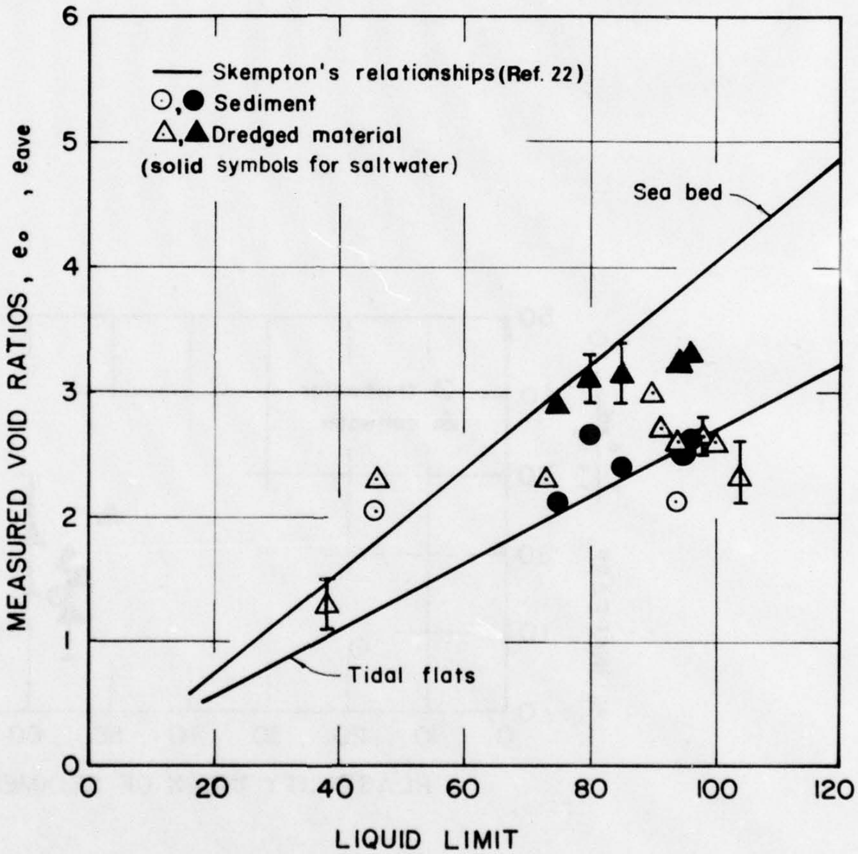

FIGURE 35. DEPOSITION VOID RATIO OF SEDIMENTS AND DREDGED MATERIALS

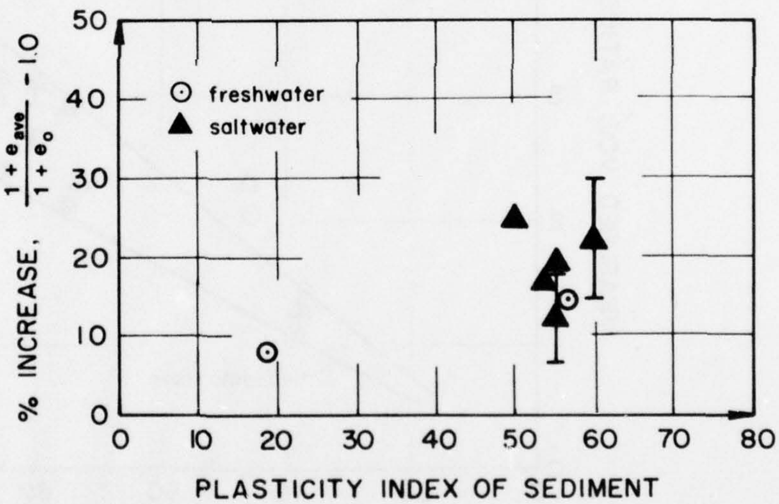

FIGURE 36. VOLUME INCREASE AFTER DREDGING AND DISPOSAL OF SEDIMENT

the volume increases due to dredging and disposal as a function of plasticity index of the sediment. The influence of the ambient water does not necessarily appear in this plot, since salinity affects both e_o and e_{ave}. The limited data in Figures 34 and 36 indicate the need for additional field data in order to provide more reliable guidelines based on observed field behavior.

PART IV: DREDGING OPERATION PARAMETERS

Introduction

94. The dredging operation involves four parameters that affect volume predictions: the overdredging factor, F_o, and the removal, transport, and containment efficiencies F_e, F_p, and F_c. Determination of these parameters can be based on experience, "best estimates," past case studies, and field measurements. Control of the dredging and/or containment operation can also "assign" values to these variables, especially with respect to losses of material.

Definition of Parameters

95. During a dredging operation, both solids and liquids are gained and lost due to the dredging process. Evaporation, rains, and waves can affect fluid volume but will not significantly change the amount of solids (if adequate freeboard is provided) and will not be considered in this analysis. Four parameters affect the volume of solids handled in the containment system: gains of solids resulting from overdredging and losses of solids (1) around the dredge, (2) during transport, and (3) in the disposal area.

Overdredging factor

96. Overdredging depends on:

a. The type of sediment: F_o can vary with stiffness of the sediment. Maintenance and new dredged material are likely to have different F_o values.

b. Control of the dredge position: The ability of a dredge operator becomes important.

c. Instability of side slopes and other possible local characteristics.

Figure 37 illustrates overdredging as defined in some U. S. Corps of Engineers District offices. (Private communication, 21 Dec. 1975, A. F. Pruett, Assistant Chief, USAE, Mobile, Alabama.) The Corps generally requires dredging to some depth below design level in order to maintain an adequate channel. This extra depth is usually 60 cm. In addition to this depth, the Corps will pay the contractor for removing, at his option, an additional amount of material over the bottom width only. This latter quantity also represents a depth of 60 cm and is called allowable overdepth. Below this depth, the work is not paid for. Since the contractor cannot dredge up side slopes, paid cross sections consider a box cut equivalent to the shoal quantity at the cross section. Overdredging involves the quantity of removed material for which payment will not be made and is shown as cross-hatched in Figure 37. Volume of sediment to be dredged should therefore include expected paid overdepths removed by the contractor. In the Mobile District, overdredging factors backfigured from four dredging jobs varied from 31 to 78 percent, as listed in Table 11.

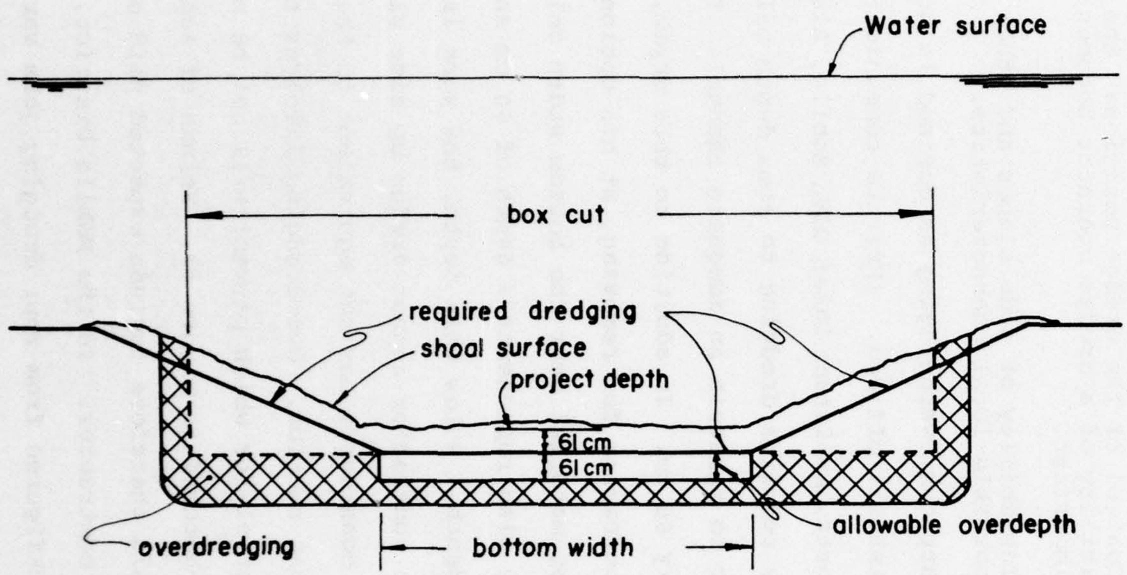

FIGURE 37. OVERDREDGING IN CHANNEL CROSS SECTION

Table 11

Examples of Overdredging Factors and Volumes of Sediment Dredged in Mobile District

Location	Dates of Maintenance Dredging	Volume of Sediment Removed and Paid for m^3	Total Volume of Sediment Removed m^3	Average Overdredging Factor, F_o %	Range of Overdredging Factor %
Mobile Bay Channel	1966-1973	23,558,679	31,093,281	32	20-64
Gulfport Ship Channel	1966-1971	12,894,752	16,934,445	31	20-78
Pascagoula Approach and Ship Channels	1964-1972	5,728,130	8,287,627	45	22-70
Pensacola Bay to Mobile Bay to Rigolets	1963-1974	4,184,271	7,469,979	78	42-235

Efficiency of operation

97. For dredging currently done in the U. S., not all solids from the in situ sediment enter the mouth of the dredge; losses due to agitation or suspension of soil particles occur during removal. Values for the removal efficiency factor, F_e, depend on the type of sediment, the type of removal, the pumping rate, the rate of advance of the cutting tool, soil density, and tidal velocity. Specific values of F_e are generally determined from experience. These are discussed in Table 12.

98. Solids can also be lost during transport from the dredge to the disposal area as a result of leaks or breaks in the pipeline. Values of the transport efficiency factor, F_p, depend on the amount of control exercised over the dredging contractor and the type of sediment. For large well-run operations, F_p will likely approach 1.0. Requirements for F_p equal to 1.0 could be established in dredging contracts.

99. The efficiency of the containment system, F_c, depends on the amount of solids lost from the containment structure and the amount of solids discharged through the effluent weir. Considerable material may be lost if dike freeboard is not sufficient to prevent breaching. Choice of adequate weir outflow and slurry inflow rates as a function of containment size and settling of solids should help keep F_c high.

Solids concentration

100. Solids concentration, Y_t, is the percent by weight

Table 12

Estimate of Dredging Operation Parameters by Selected Corps of Engineers and Dredging Specialists

Source of Information	Overdredging Factor, F_o %	Removal Efficiency, F_e %	Transport Efficiency, F_p %	Containment Efficiency, F_c %	Solids Concentration % by weight	Comments
Buffalo District	10	100	100	100 *	10-25	Hopper dredges
Norfolk District	30-35	100	100	100 *	--	$F_e \neq 100\%$ if very strong tides
Mobile District	30-78	80-100	>98	--	--	F_o backfigured from past jobs
Detroit District	0-10	>95	>98	100 *	--	F_c decreases at end of operation, $F_p > 98$ if inspector present
New England Division	10	>95	>95	--	--	
Seattle District	10(in silt) 0(in clay)	100	100	?	20(in sand) 18(in silt)	
Philadelphia District	--	100	100	100	--	
Galveston District	10-25	>98	>90	>95	12-15	
J. Huston	10	>98	>98	>95	--	
Port & Harbour Tech. Res. Inst., Japan	--		$F_e F_p F_c = 81$		--	Average value backfigured from 3 cases in Japan
Average	24	97	97	86	16	
Best-Estimate	20-30	97	100	98	15	Need inspection and control
Significant Factors	Operator Sediment Job Equipment	Operator Sediment Tides	Inspector Contractor Slurry Equipment	Environmental specifications Flow rate Weir design Freeboard	Dredging method Sediment Cutter action Agitation	

* Future requirement

of solids in the slurry entering the area. At the present time, estimation of solids concentration, relying on experience and limited field measurements, remains approximate. It is out of the scope of this report to determine the factors influencing the solids concentration of the material entering the area.

Review of Current Practice

101. The authors consulted selected Corps of Engineers and dredging specialists for dredging operation parameters as shown in Table 12. Numbers were generally based on experience. The average "best estimates" offered by all the specialists and as compiled by the authors indicated that the overdredging varied between 20 and 30 percent and that overall losses (during removal and transport and from the containment system) were less than 5 percent (F_e = 97 percent, F_p = 100 percent, F_c = 98 percent). Solids concentrations averaged 15 percent, by weight. Table 12 also summarizes the average and best estimate of each dredging operation parameter and lists the variables affecting each of them.

Field Observations

102. The authors measured the dredging operation parameters in the Cleveland Harbor, Branford Harbor, and James River-Windmill Point disposal sites and observed qualitative losses at several other containment areas. Whereas overdredging has

to be backfigured and cutterhead efficiency was difficult to assess, losses both during transport and from the containment system have been observed in many cases. However, transport losses were never very large (estimated as less than 5 percent by weight of the solids dredged in the channel). On the other hand, losses at the weir have sometimes been very high.

103. Solids concentration does not enter in the prediction methodology equation as such, but affects settling rates of the dredged material. In Cleveland Harbor, measured solids concentration in the slurry directly from the inflow pipe ranged from 10 to 25 percent solids by weight.

Recommendations

104. The selection of an overdredging factor should be based on local experience along a particular channel reach to be dredged. The authors recommend using an overdredging factor between 0 and 30 percent, with the value decreasing with increasing sediment strength. For smaller jobs, slightly larger F_o values can be used. Very strong winds or tides during dredging can decrease the removal efficiency, F_e, by 5 or 10 percent. Otherwise, F_e should remain near 100 percent. The authors recommend using F_e = 95 percent, F_p = 100 percent and F_c = 100 percent in the sizing methodology unless local conditions indicate different values. The volume of sediment to be dredged should consider expected overdepths paid to the contractor since these are not included in the overdredging factor.

Summary

105. In the sizing equation, the product $F_eF_pF_c$, as recommended, is 0.95. On the other hand, F_o can go from 0 to 30 percent. If Equation 4 is rewritten such that

$$V_{CA} = Z(1 + F_o)F_eF_pF_c \tag{10}$$

where Z replaces $\frac{V_t(1 + e_{ave})}{(1 + e_o)}$ and is considered as invariant, the effects of the dredging operation parameters on the required volume can be obtained. The uncertainty due to the overdredging factor, F_o, can alter the value of $(1 + F_o)F_eF_pF_c$ from 0.95 to 1.24.

PART V: APPLICATIONS OF THE PREDICTION METHODOLOGY

Introduction

106. In Part V the authors apply the prediction methodology to four disposal sites:

a. Cleveland Harbor disposal site nos. 1 and 2.

b. Cleveland Harbor disposal site no. 12.

c. Branford Harbor upland disposal site.

d. Anacortes.

The information necessary for the solution of the sizing equation at each disposal site was not always available. In such cases, engineering judgment and experience with other dredged materials were used. Appendix A describes the layout and investigations at each disposal site. When pertinent, the applications consider the following four components: the channel sediment, the dredging operation, the dredged material, and foundation settlements. Predicted containment volumes are then compared to field performance, when available.

Cleveland Harbor

107. Disposal sites nos. 1, 2, and 12 in Cleveland Harbor, built in the waters of Lake Erie, contain dredged material from a freshwater environment. Figure 38 shows a

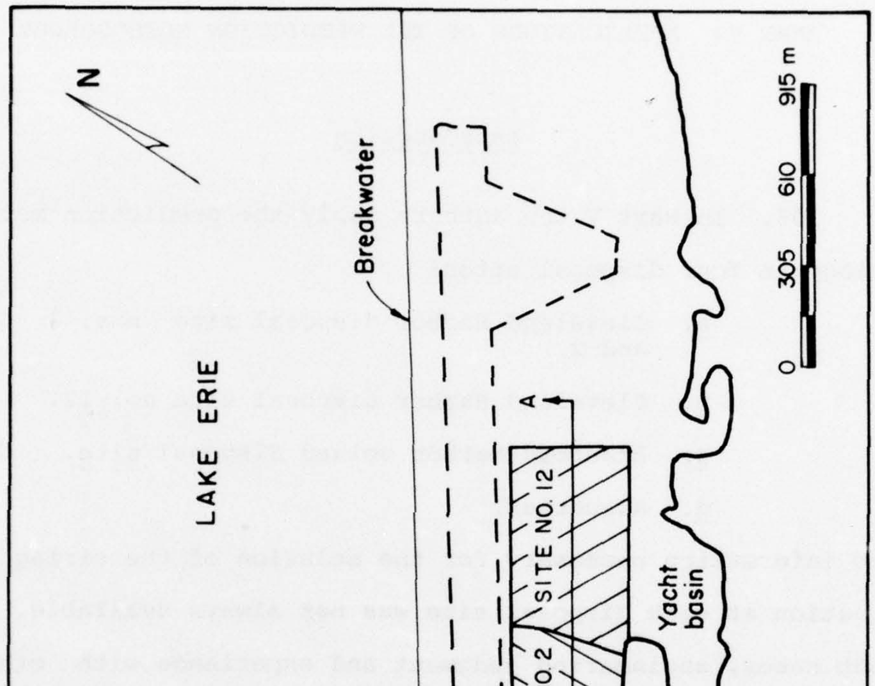

FIGURE 38. DISPOSAL SITES IN CLEVELAND HARBOR

plan of the vicinity of the sites and Figure 39 the planar dimensions. In experimental site nos. 1 and 2, filling lasted from 1968 until 1973. In area no. 12, filling started in 1975. This last area was designed to contain also the material from 1976 and 1977 maintenance dredging of both the harbor and Cuyahoga River channel.

108. Application of the sizing methodology in Cleveland Harbor involved three steps:

a. Prediction of the required containment volume in area nos. 1 and 2 and comparison with actual performance.

b. Prediction of the required containment volume in area no. 12 for the material dredged between April and December 1975 and comparison with actual performance.

c. Sizing of area no. 12 (height only, since horizontal dimensions are fixed) to contain the projected material dredged until 1977.

Area nos. 1 and 2

109. In area nos. 1 and 2 (see Appendix A for further details), the dredged material was 3.66 m above low water datum. Based on yearly channel surveys, the total volume removed by hopper dredges was 2,172,030 m^3, approximately 25 percent more than the expected design volume of 1,727,830 m^3. Freeboard on the dikes averaged 76 cm. However, during disposal, two storms swept over the disposal sites and some loss of solids may have occurred. But no reliable quantity measurements could be made. The total planar area was 217,385 m^2.

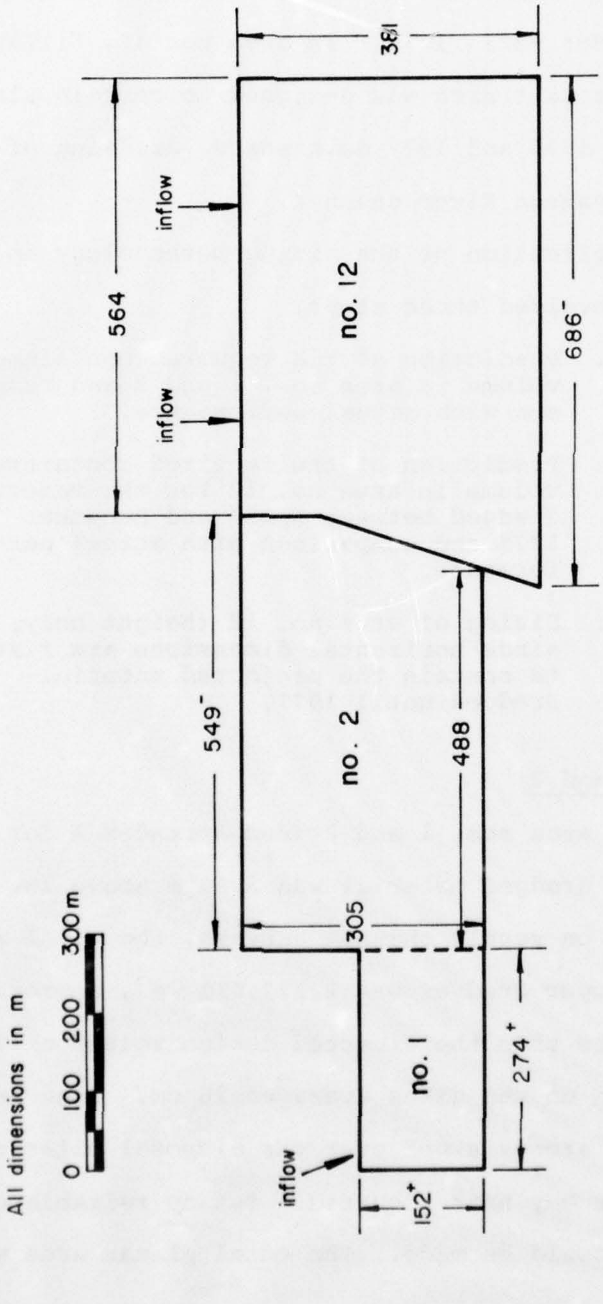

FIGURE 39. DIMENSIONS OF CLEVELAND HARBOR DISPOSAL SITES

110. Figure 40 shows the profile through area nos. 1 and 2. The ground surface of the dredged material was essentially horizontal, but the original lake bottom sloped gently eastwards. The average depth of dredged material was 9.75 m in site no. 1 and 10.35 m in site no. 2. The total storage volume available was therefore 2,395,840 m^3.*

111. All areas contained sediment from Cleveland Harbor and Cuyahoga River. The in situ void ratio, averaged over several years was measured as 2.05. It should be noted that if actual volume in hoppers were used to determine the volume of material dredged, the in situ sediment void ratio would no longer apply since the material may occupy a different volume in the hopper dredge. In the relatively soft Cleveland sediment, some overdredging is expected, but the efficiency of the operation (done by Corps of Engineers' and contractor's hopper dredges) should be high. The product $F_e F_p F_c$ was selected as 0.95 as losses from the hopper, during transport, and from the containment system could occur. Since dredged volume estimates were actual volumes dredged, the overdredging factor is zero.

112. The Corps of Engineers measured the average void ratio of the dredged material in site no. 1 and consistently obtained 2.30 over several years. Site no. 2 contained material very similar to the material in area no. 1 (Personal

*All volumes rounded off to nearest 5 m^3.

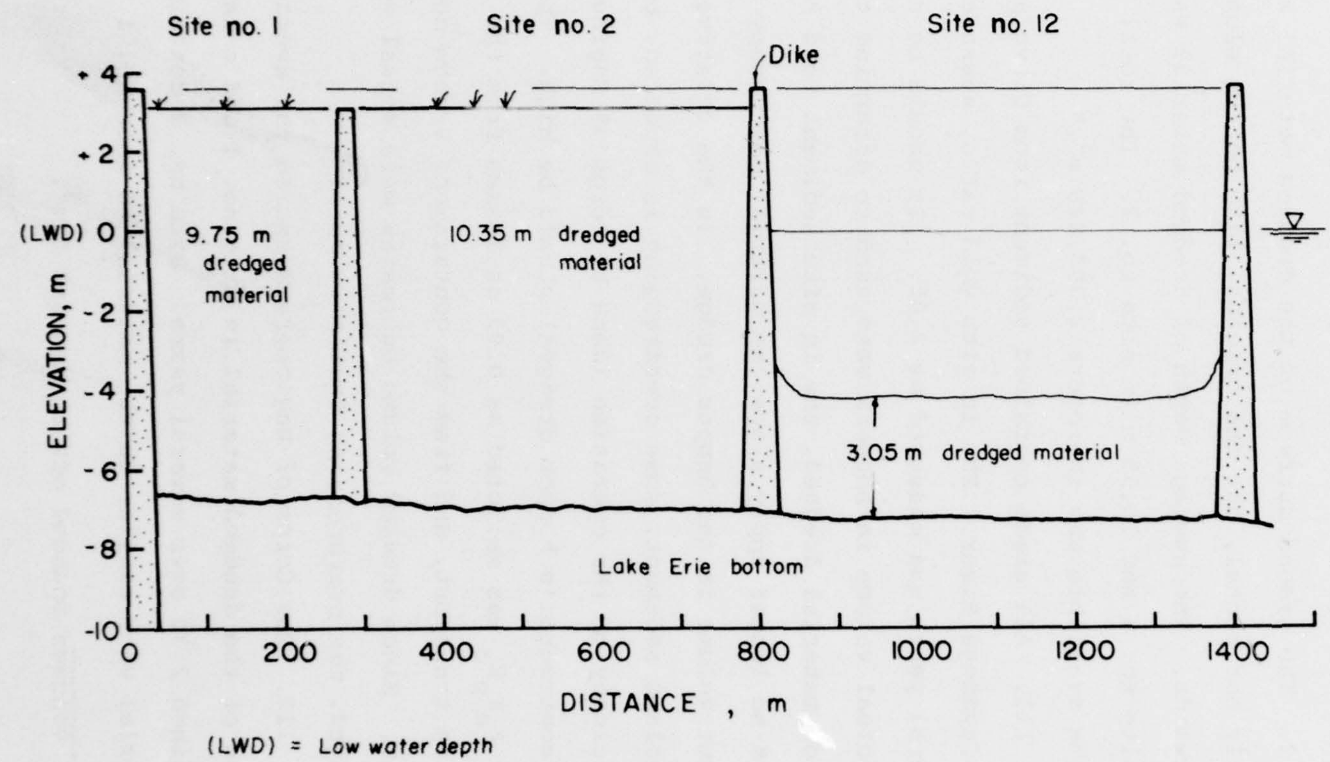

FIGURE 40. CROSS SECTION THROUGH CLEVELAND HARBOR DISPOSAL SITES

Communication, 9 March 1976, G. E. Greener, Construction-Operation Division, Corps of Engineers, Buffalo District, New York). Since no other data were available, the value of 2.30 for e_{ave} was selected for the combined area nos. 1 and 2 (see Part III).

113. Applying Equation 4, the predicted containment volume, V_{CA}, becomes:

$$V_{CA} = \frac{2,172,030 \times 0.95 \times 1.00 \times 3.30}{3.05} \ m^3$$

$$V_{CA} = 2,232,560 \ m^3$$

The method underestimates the storage volume by 9 percent. However, if one computes volume increases through the relationship:

$$\text{Volume increase} = \frac{1 + e_{ave}}{1 + e_o} - 1.00 \qquad (7)$$

where e_{ave} = average void ratio of dredged material

e_o = in situ void ratio of channel sediment,

the measured data show that no swell occurred at disposal site nos. 1 and 2. This is believed incorrect and can probably be explained by an appreciable loss of solids during stormy weather. Consideration of these losses (if it were possible) would reduce V_t, V_{CA}, and the relative error on predicted volume. For example, if 5 percent of V_t had been lost during the storms, the measured swell of the dredged material would increase to 5 percent, but the sizing method would now underpredict the volume by only 3 percent. Whereas, the authors do not know what effective loss occurred, the analysis shows that the results of the sizing procedure remain very sensi-

tive to a reliable assessment of the volume of sediment (slurry) actually in the disposal site and the void ratios selected for sediment and dredged material.

Area no. 12, 1975

114. During the eight dredging months in Cleveland Harbor in 1975, the hired contractor and the Corps of Engineers dredges removed 742,910 m^3 of sediment (based on channel surveys). The average thickness of the dredged material below 5 m of water was 3.05 m (see Appendix A for profiles). Using again

$$e_o = 2.05$$

$$F_o = 0\%$$

$$F_e F_p F_c = 0.95$$

$$e_{ave} = 2.3 \text{ (from Figure 24)},$$

the predicted versus measured containment volumes as well as volume increases agreed very well, as listed in Table 13.

Future disposal in area no. 12

115. The total project volume to be disposed of in area no. 12 is 2,102,450 m^3. However, the allowed over-depth will probably be also removed and approximately 5 percent of the total volume of sediment should be also included in V_t. Local experience suggests 20 percent overdredging as common. Substituting in Equation 4, the e_o, e_{ave}, F_e, F_p, and F_c values discussed earlier, the predicted volume occupied by the dredged material will be 2,722,915, m^3. Given the planar area of site no. 12, the

Table 13

Application of Sizing Methodology

Parameter	Cleveland Harbor Area nos. 1 and 2	Cleveland Harbor Area no. 12(1975)	Cleveland Harbor Area no. 12(Future)	Branford Harbor Upland Site	Anacortes Site
Volume to be Dredged, V_t m^3	2,172,030	742,910	2,102,450 + 5% allowed overdepth	72,500 + 15% allowed over-depth	383,755
In Situ Void Ratio, e_o	2.05	2.05	2.05	2.50	SM = 0.90 ML = 1.80 CH = 2.25 Avg = 1.94
Overdredging, F_o %	0	0	20	30	15
Efficiency, $F_eF_pF_c$	0.95	0.95	0.95	0.90	0.97
Average Void Ratio of Dredged Material, e_{ave}	2.30	2.30	2.30	3.20	SM = 0.90 ML = 2.30 CH = 3.00 Avg = 2.52
Predicted Containment Volume, V_{CA} m^3	2,232,560	763,615	2,722,915	117,060	512,530
Measured Containment Volume, V_{CAM} m^3	2,039,400	725,590	---	---	535,170
Relative Error on Predicted Volume %	+9	+5	---	---	-4

thickness of the dredged material will be 11.4 m.

116. The final consolidation settlement of the foundation can be computed with the following relationship:[23]

$$\rho = \sum_{i=1}^{n} H_i \left(\frac{C_r}{1 + e} \log \frac{\bar{\sigma}_{vm}}{\bar{\sigma}_{vo}} + \frac{C_c}{1 + e} \log \frac{\bar{\sigma}_{vf}}{\bar{\sigma}_{vm}} \right) \qquad (8)$$

where ρ = settlement

H_i = thickness of layer i

n = number of layers

C_r = recompression index

C_c = compression index

e = initial void ratio in layer i

$\bar{\sigma}_{vm}$ = maximum past pressure

$\bar{\sigma}_{vo}$ = in situ vertical effective stress

$\bar{\sigma}_{vf}$ = final vertical effective stress

117. Using the profile and soil properties of Lake Erie bottom shown in Figure 41 and average total unit weights of 1.5 g/cc for the dredged material and 2.0 g/cc for the dike material, settlements of 100 cm in the center of the disposal site and 150 cm under the dikes were obtained if foundation was considered normally consolidated (n.c.). The settlements reduced to 50 cm and 100 cm, respectively, when the top of the deposit was considered overconsolidated. However, since the permeability for the silty clay foundation is probably low, most consolidation settlement will not have time to occur in the three-year planned usage. It would therefore seem that the dike freeboard as designed will be insufficient.

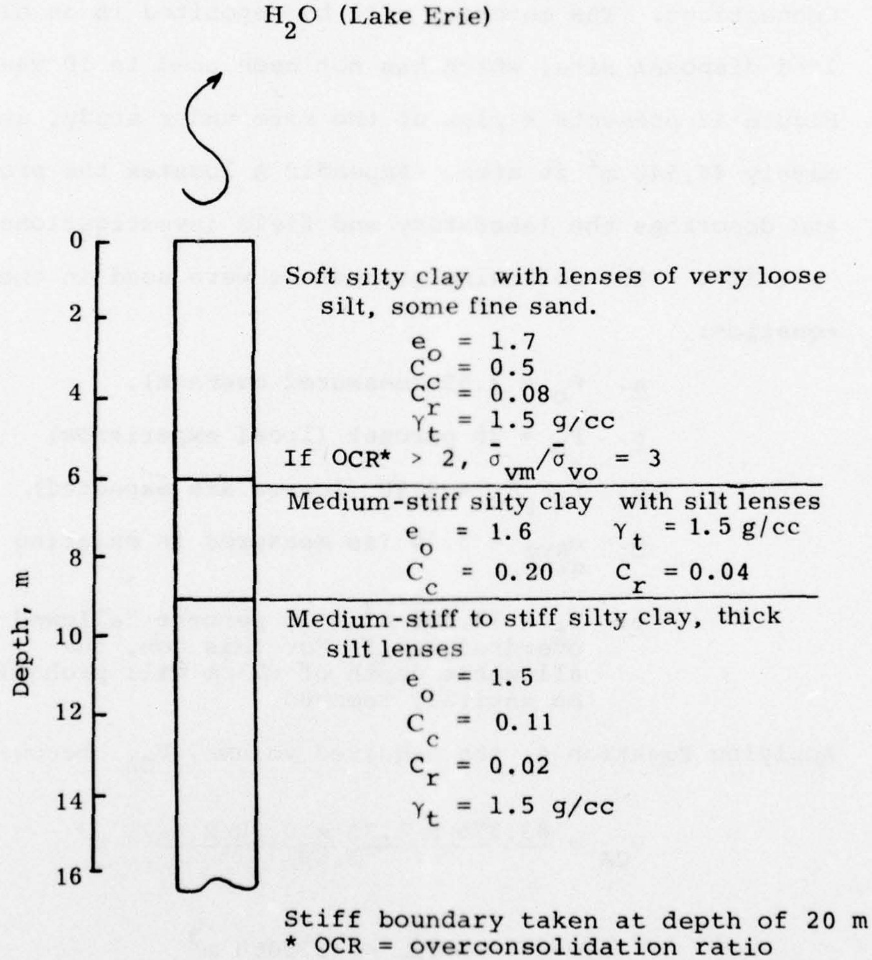

Figure 41. Sediment profile underlying Cleveland Harbor disposal sites

Branford Harbor

118. In September 1976, the New England District dredged approximately 72,500 m^3 of sediment in Branford, Connecticut. The material will be deposited in an old upland disposal site, which has not been used in 10 years. Figure 42 presents a plan of the site under study, approximately 44,540 m^2 in area. Appendix A locates the project and describes the laboratory and field investigations.

119. The following parameters were used in the sizing equation:

a. e_o = 2.50 (measured average).

b. F_o = 30 percent (local experience).

c. $F_e F_p F_c$ = 0.90 (losses are expected).

d. e_{ave} = 3.20 (as measured in existing site.

e. V_t = 72,500 m^3 + 15 percent "allowed overdredging." For this job, the allowable depth of 60 cm will probably be entirely removed.

Applying Equation 4, the required volume, V_{CA}, becomes:

$$V_{CA} = \frac{83,375 \times 1.30 \times 0.90 \times 4.20}{3.50} \ m^3$$

$$V_{CA} = 117,060 \ m^3$$

This volume implies a 2.6 m thickness of dredged material in the upland disposal site.

120. Figure 43 presents the profile and stress history used in the foundation settlement analysis. No complete

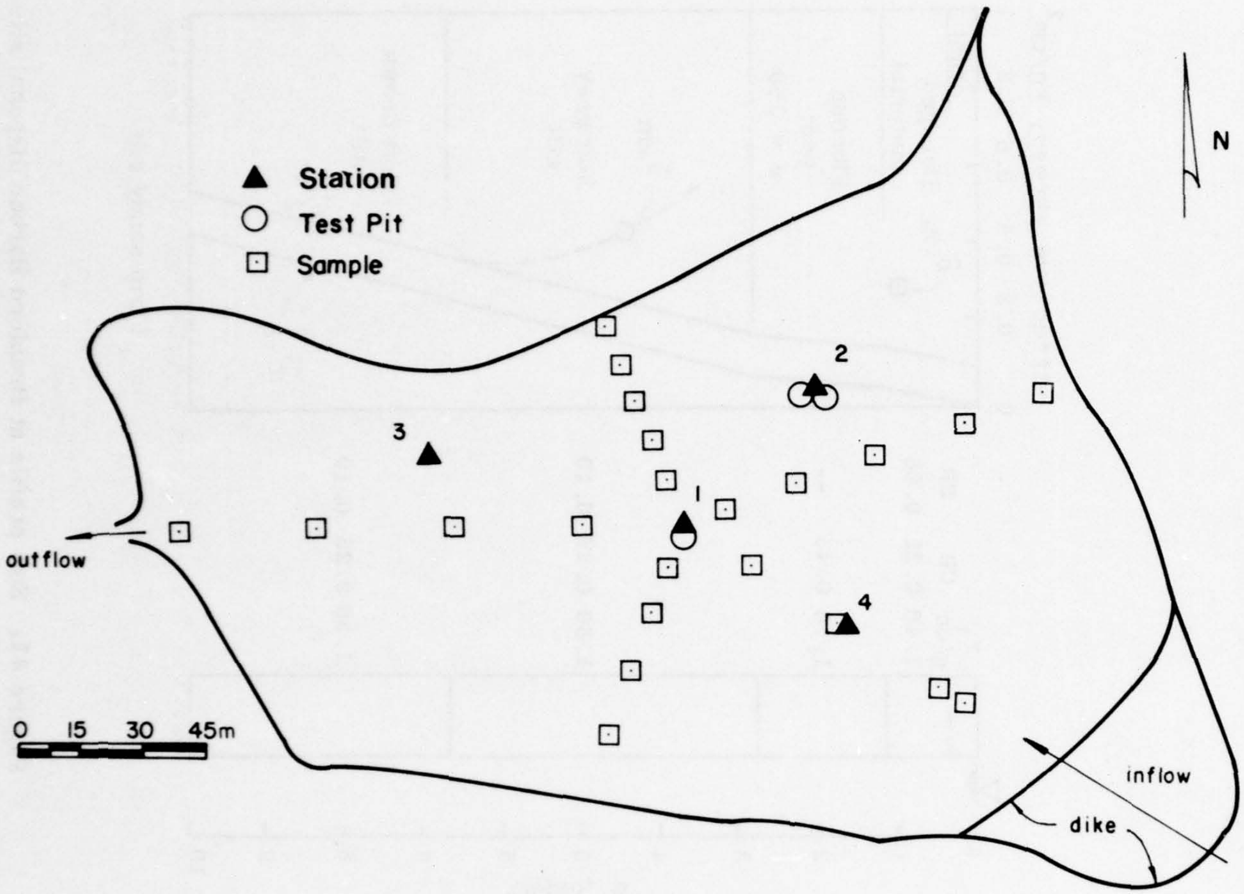

FIGURE 42. BRANFORD HARBOR UPLAND DISPOSAL SITE

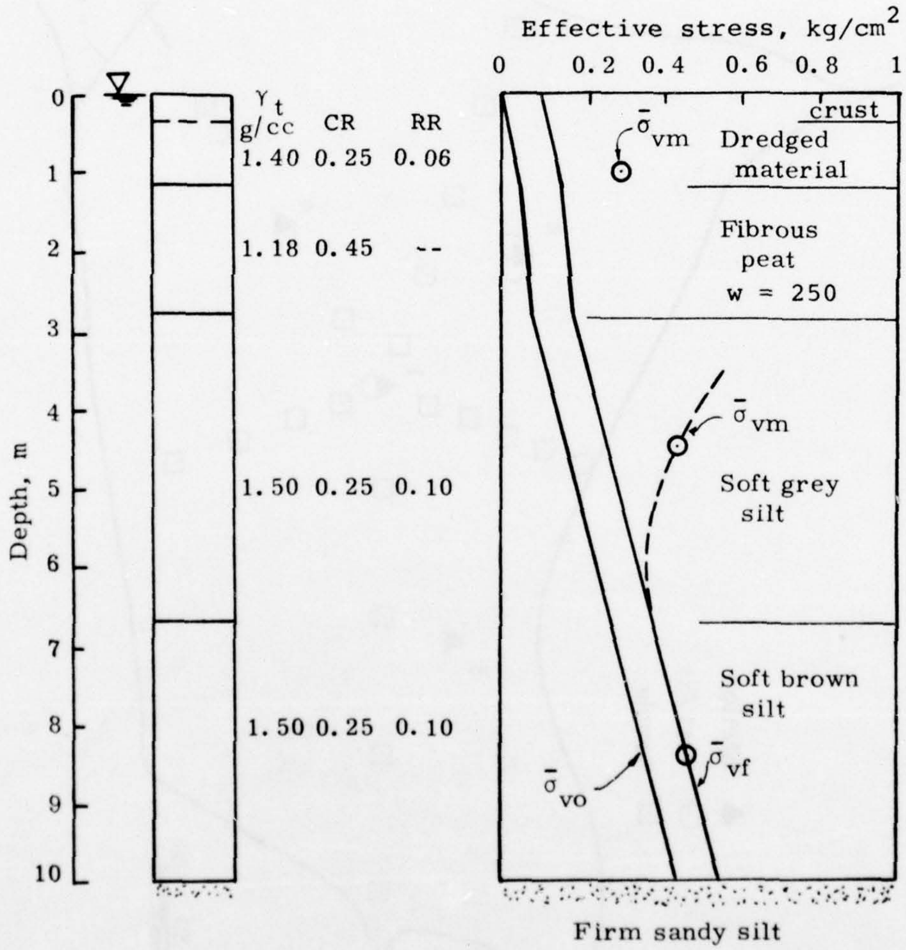

Figure 43. Soil profile at Branford Harbor disposal site

borings of the foundation material underlying the upland disposal area were available. Test pits in the previously dredged material exposed 1.3 m of highly plastic organic silty clay, brown at the surface and gradually changing to dark-grey. The lighter surface material appeared desiccated with numerous fissures. One consolidation test on a sample from a depth of 1 m yielded a recompression ratio, RR,* of 0.059; a virgin compression ratio, CR,* of 0.25; and a maximum past pressure of 0.3 kg/cm^2. Analysis of material from a tube sample extending below the test pit (1.3-2.0 m) indicated a layer of fibrous, non-decomposed peat. Ladd[23] reported values of CR = 0.45 for peats occurring at natural water contents of 250 percent.

121. Samples from the harbor foundation indicated 4 m of dark-grey, soft organic silt with shells overlying 3.3 m of dark-brown, soft organic clay founded by firm sandy silt. Consolidation tests of the dark-grey silt yielded a recompression ratio, RR of 0.10 and a virgin compression ratio, CR, of 0.145. Tests on the brown silt indicated similar results. The average total unit weight of the 2.60 m-thick-dredged material was selected as 1.4 g/cc. The maximum effective stress increase was, therefore, 0.10 kg/cm^2 at the fibrous peat-dredged material interface. Using Equation 8, a foundation settlement of 15 cm was obtained.

122. However, in the short time available for disposal, little consolidation settlements are expected. The foun-

*NOTE: $RR = C_r / 1 + e$ and $CR = C_c / 1 + e$.

dation settlements for sizing purposes are, therefore, negligible. The dredged material in the disposal site will have a thickness of 260 cm above the elevation of the site after dike construction by the contractor.* Table 13 summarizes the prediction.

Anacortes

123. In the Anacortes disposal site, shown in Figure 44, both containment volume and volume of sediment effectively in the disposal area were measured, but the average void ratio of the dredged material was unknown. However, the geotechnical properties discussed in Part III and the site and material descriptions in Appendix A gave an indication of the possible behavior.

124. The volume of saltwater sediment dredged (based on Seattle District records) was 404,230 m^3, but 20,475 m^3 were lost over the weir at the end of the operation. The effective volume of sediment, $V_t F_c$, in the disposal site was 373,755 m^3. Based on the site and profile descriptions in Appendix A, the channel sediment included three soil types, called for the present purposes "sand" (SM), "silt" (ML), and "clay" (CH). Figure 45 shows the grain sizes of

*Considers no swelling of the foundation upon removal of material by the contractor for dike construction.

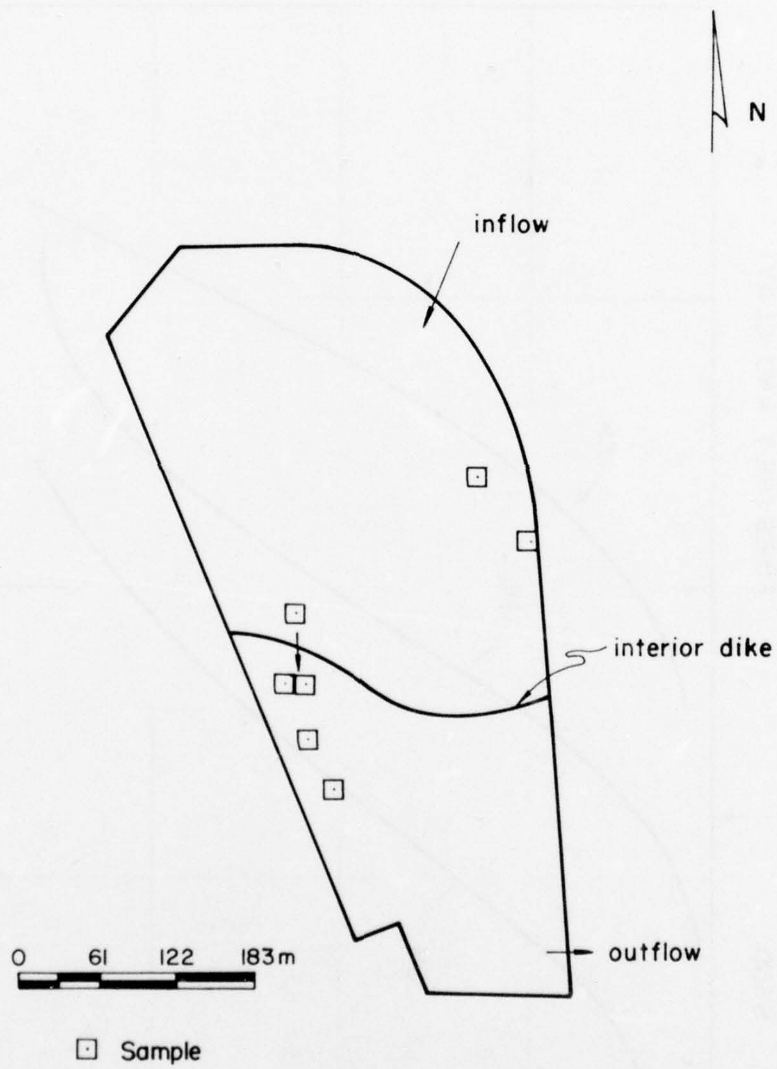

FIGURE 44. ANACORTES DISPOSAL SITE

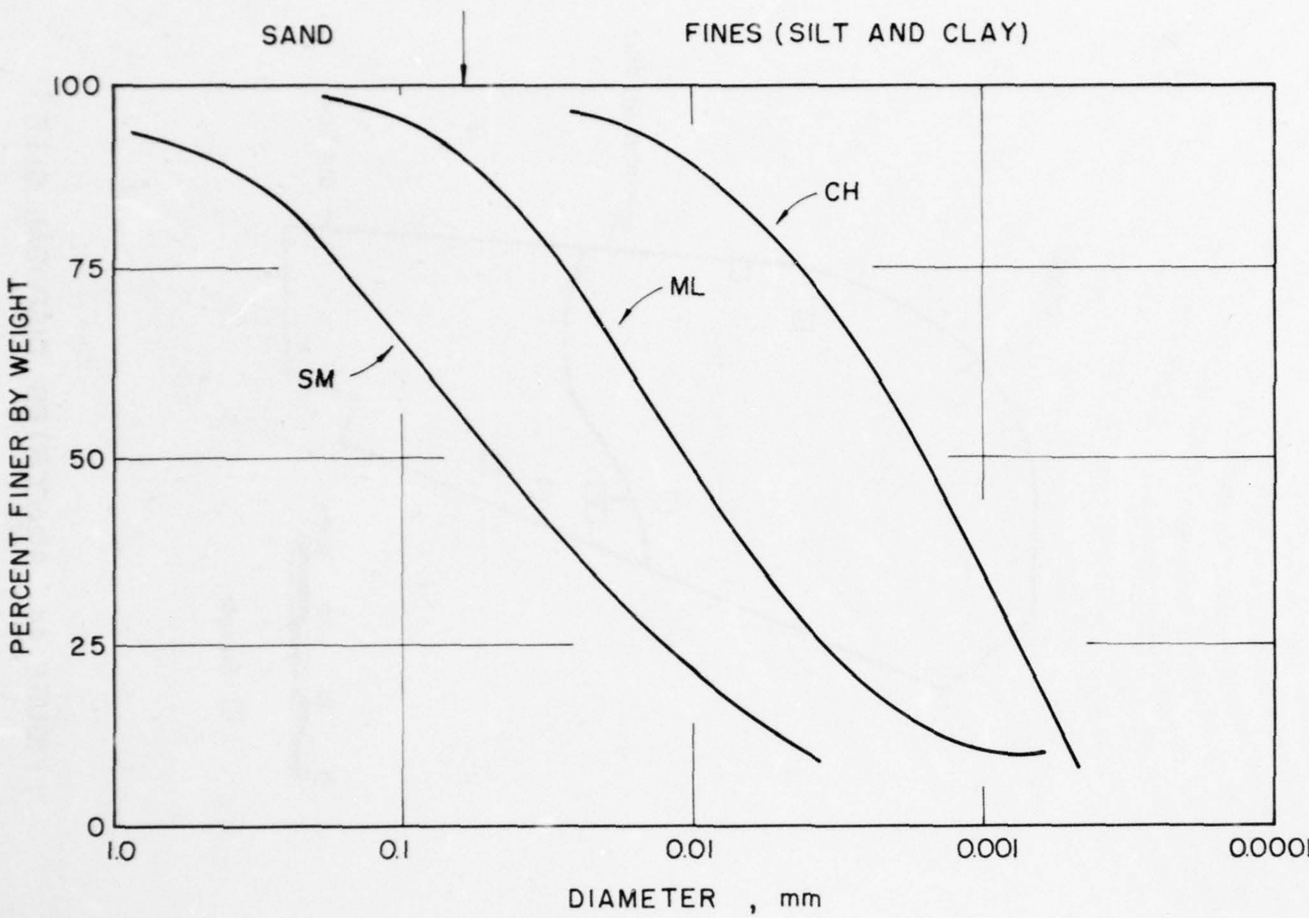

FIGURE 45. GRAIN-SIZE DISTRIBUTION OF ANACORTES SEDIMENT

the three materials and Table 14 describes their characteristics. Atterberg limits were available only on the CH material: $w_l = 72$, $w_p = 28$, and $I_p = 44$. The in situ void ratio of the sand was 0.89; however, measurements in the other two types of soil were not available. Profiles at various cross sections of the channel to be dredged (Appendix A) indicate the following proportions of SM, ML, and CH materials in the sediment dredged:

a. sand (SM) = 5%

b. silt (ML) = 53%

c. clay (CH) = 42%

125. Based on Figures 4 and 34, and on Tables 9 and 10, the following void ratios were assigned to the sediments.

Sediment	In Situ Void Ratio, e_o
Sand (SM)	0.9
Silt (ML)	1.8
Clay (CH)	2.25

Table 14 lists the reasons underlying these choices. The weighted average void ratio equals 1.94. A weighted average void ratio can be used only under very particular field conditions, where different types of material exist in separate states along different reaches of the channel and are not

Table 14

Void Ratios of Anacortes Channel Sediment and Dredged Material

Material Description	In Situ Void Ratio e_o	Explanation	Average Void Ratio e_{ave}	Explanation
Loose to medium-coarse sand with silt, some gravel (SM)	0.90	-Measured average e_o (Figure 4)	0.90	-Inorganic material -No swell expected
Soft to medium organic silt with shells, low plasticity (ML)	1.80	-Grain-size curve (Figure 2) -I_p must be low ($\leq$ 15) (Figure 34) -Saltwater environment	2.30	-Grain-size near that of Browns Lake -Use Figure 34 -Some organic content -Saltwater environment
Stiff to very stiff highly plastic silty clay, occasional sand or gravel, organic matter (CH) $w_1 = 72$ $I_p = 44$	2.25	-Figure 35 (w_1=72) -Figure 34 (I_p=44) -Very stiff sediment -Grain-size curve (Figure 2) -Saltwater environment	3.00	-High percentage of fines -I_p=44 (Figure 34) -Saltwater environment

intermixed. The procedure would not be applicable if the channel sediment actually contained a mixture of the various materials.

126. Little overdredging is expected. F_o was selected as 15 percent. The prediction used the recommended value for parameter F_e (F_e = 0.97), but increased F_p to 1.00 since no long pipelines were required for transport of slurry. The parameter F_c has already been taken into consideration in the effective volume of channel sediment-retained computation.

127. The average void ratio for each component of the saltwater dredged material and the weighted average for the dredged deposit were selected as shown in Table 14. Compared to the in situ sediment void ratios, these values imply an overall volume increase of 20 percent upon disposal in the Anacortes disposal site (after sedimentation and self-weight consolidation). Using an average total unit weight of 1.5 g/cc for the dredged material, the effective stress increase on the foundation varies from 0.18 to 0.42 kg/cm^2.* No geotechnical properties of the foundation (shown in Figure 46) were available. Since the stiff foundation has a low compressibility, the foundation settlements during disposal will be negligible, compared with the total containment volume.

128. Application of Equation 4 leads to the required

*Original ground elevation in area varied between -1.2 and +3.1 m (datum at MLLW).

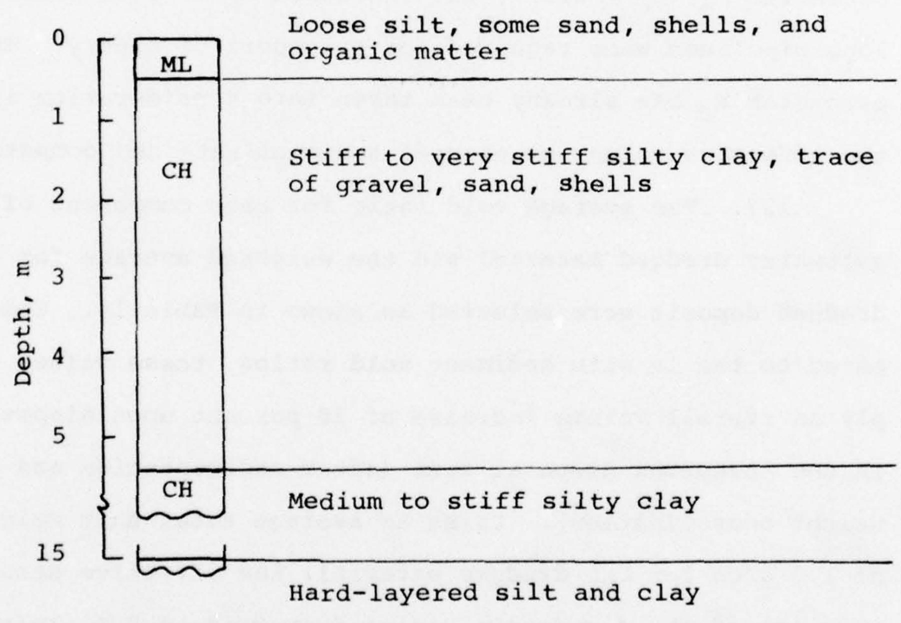

Figure 46. Foundation of Anacortes disposal site

containment volume, V_{CA}:

$$V_{CA} = \frac{383{,}755 \times 1.15 \times 0.97 \times 3.52}{2.94} \ m^3$$

$$V_{CA} = 512{,}530 \ m^3$$

The measured containment for 383,755 m^3 of sediment was 535,170 m^3. The predicted volume is therefore unsafe by 4 percent. Adequate design would require also additional dike height for adequate freeboard. The discrepancy between measured and predicted containment volumes could be due to the following reasons.

a. Uncertainty in e_{ave} for both the silt and clay portions of the material.

b. Predicted dredged material void ratios apply to end of self-weight consolidation conditions. However, the measured storage volume was taken immediately after disposal, and consolidation of the more recent dredged material may not have been completed.

c. Rough estimates of proportions of sand, silt, and clay materials in sediment.

d. Incorrect estimates of F_o, F_e, F_p and F_c.

e. Difficulty in calculating the storage volume of the containment area (due to the uneven original surface).

Table 13 summarizes the parameters used for the prediction.

Summary

129. Part V has shown how to use the prediction method. In some cases, very little data were available, but correlations with other dredged material provided estimates for the missing data. In the three instances where predicted and measured volumes were compared, the results were generally satisfactory. This procedure therefore reduced the uncertainty associated with containment volumes determined from traditional sizing techniques as illustrated in Part VI. Comparison of measured versus predicted volumes in Cleveland Harbor disposal sites agreed amazingly well. However, sufficient freeboard will not be available if the three-year design sediment volume is disposed in area no. 12. Careful monitoring at the end of the yearly filling operation is therefore recommended in order to prevent major solid losses by overtopping.

PART VI: GUIDELINES FOR SELECTION OF SIZING METHODOLOGY PARAMETERS

Channel Sediment

130. The void ratio of the channel sediment is a major unknown in the sizing procedure. The only good way to obtain values remains undisturbed sampling in the channel to be dredged. However, because of sampling difficulties and the water environment, even these results can present major scatter. If undisturbed samples are not available, void ratio can be estimated from water contents on disturbed samples, grain sizes, or plasticity. As shown in Figure 5, e_o increases with finer particle size and ambient water salinity and probably with degree of uniformity in grain sizes.

131. However, the best correlation properties for the in situ void ratio remain the Atterberg limits and plasticity index. Based on the data presented earlier, the authors recommend selection of e_o as a function of either I_p or w_l, if measurements are not available. Relationships are shown in Figure 47 for channel sediment. The figure distinguishes between saltwater and freshwater deposits. However, one must remember that these recommendations were based on limited data. Additional field measurements would greatly help to refine selection of e_o. On the void ratio-liquid limit plot, Skempton's lines for inorganic materials are also shown for comparison.

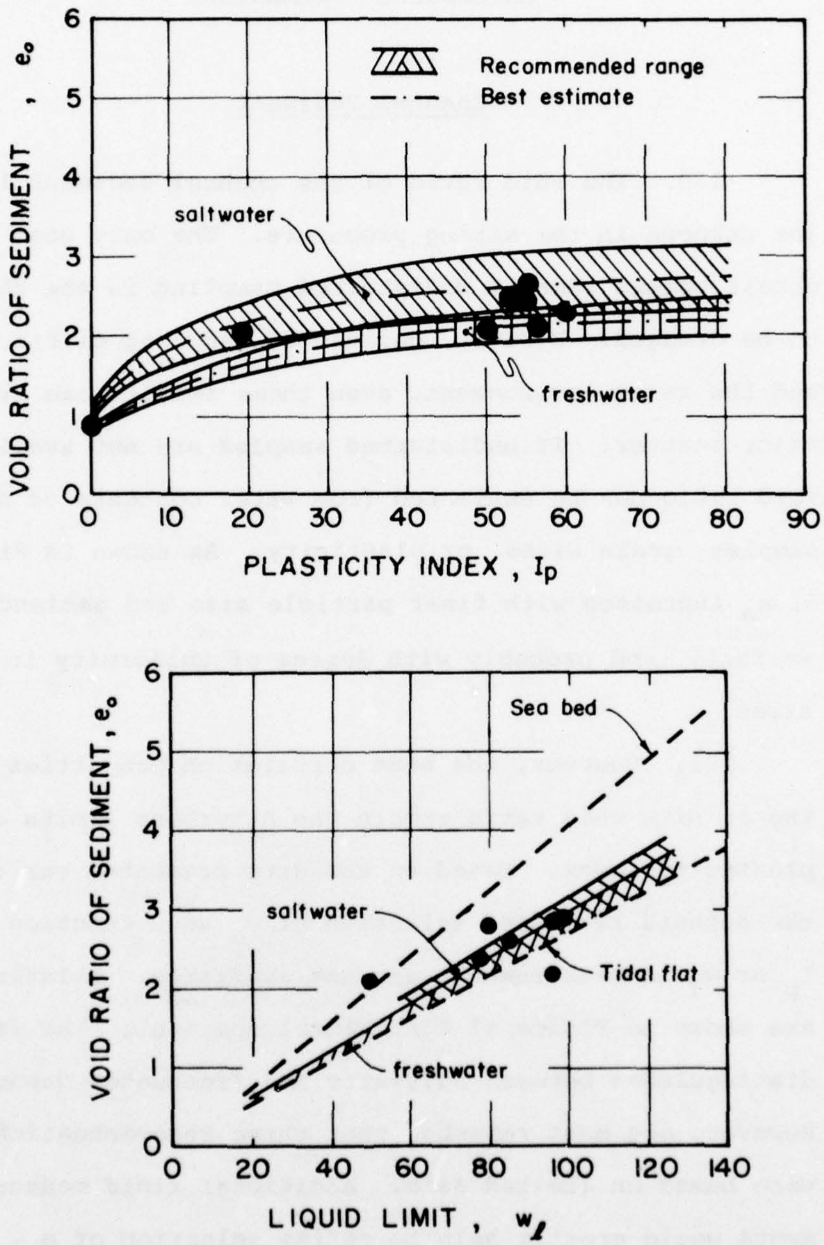

Figure 47. Void ratio and index properties of channel sediment

132. To illustrate the scatter recorded in measured e_o, each individual data point for Cleveland Harbor and Branford Harbor sediments has been plotted on dot frequency diagrams (Figure 48). In Cleveland Harbor, 82 percent of the data lie within $\bar{e}_o \pm 0.55$, where $\bar{e}_o$ is the mean in situ void ratio ($\bar{e}_o = 2.05$). In Branford Harbor, 75 percent of the data lie within $e_o \pm 0.70$ ($\bar{e}_o = 2.05$). Standard deviations are shown on the figure. The dot frequency diagrams and Figure 47 lead the authors to estimate that an average void ratio of sediment has a $\pm$ 20 to 25 percent uncertainty factor associated with it.

133. In summary, three alternatives enable one to estimate e_o: (1) obtain undisturbed samples and measure water contents, and total unit weights (to compute void ratio and degree of saturation), (2) obtain disturbed samples and measure water contents (assuming S = 100%), (3) use the correlations developed in this study. This last method should be done in three steps, if both Atterberg limits and grain sizes are available (all easily measured on disturbed samples):

a. Find e_o function of I_p and water salinity.

b. Find e_o function of w_l and water salinity.

c. Compare values of e_o and select best one from experience and perhaps by using Figure 5 where e_o is related to grain size.

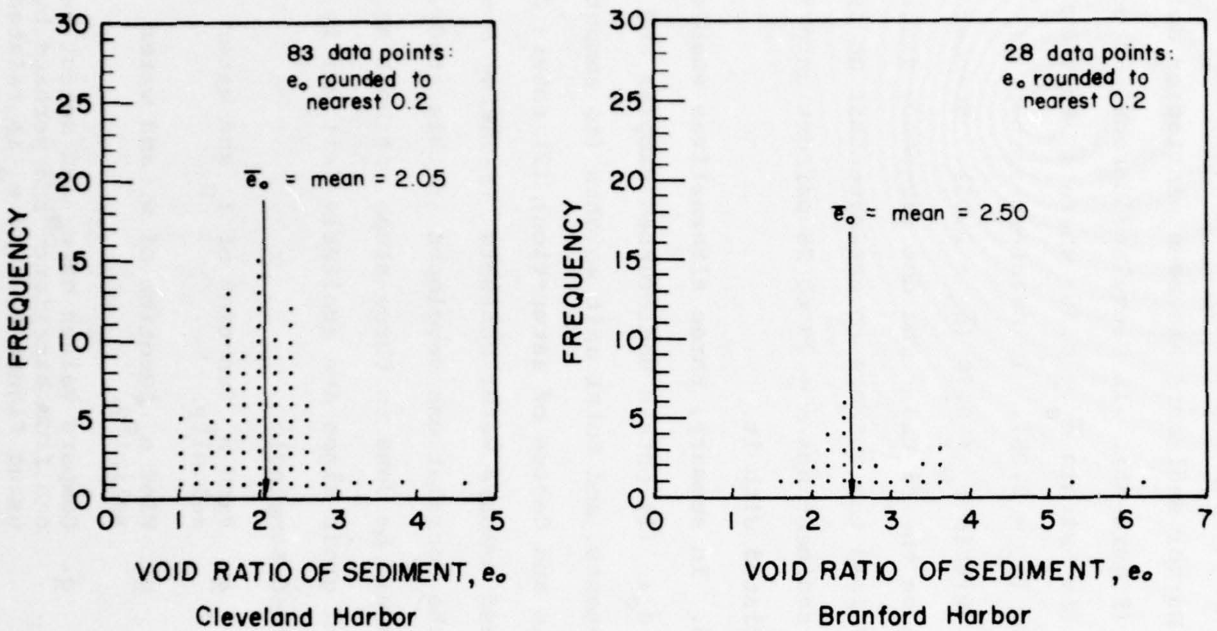

FIGURE 48. DOT FREQUENCY DIAGRAMS OF IN SITU VOID RATIO OF CHANNEL SEDIMENT

Sedimentation and Self-Weight Consolidation of Dredged Material

134. Measured void ratio of dredged material has shown much less scatter than the void ratio of the channel sediment. Predicted e_{ave} from laboratory sedimentation-consolidation tests have agreed amazingly well with field measurements. For sizing containment areas designed for multiple-year usage, the authors recommend considering the void ratio attained after sedimentation and self-weight consolidation, since dissipation of most excess pore pressures will occur during and between dredging seasons. Full dissipation of pore pressure will increase the effective stress in the dredged material, but as pointed out previously, the void ratio does not vary appreciably in the 0.005 - 0.1 kg/cm^2 stress range. Means of assessing e_{ave} include (1) laboratory tests and (2) as for e_o, correlations with plasticity index and/or liquid limit.

135. Laboratory column sedimentation-consolidation tests remain the best way to predict e_{ave}. Tests performed at MIT have shown that the results are both repeatable and reliable (see Part III). If these are not available, Figure 49 shows the relationship between e_{ave} and index properties. No information was available for saltwater sediments with low I_p's. The authors estimate the uncertainty on e_{ave} on the order of $\pm$ 10 to 15%.

136. The void ratios shown in Figure 47 and 49 allow

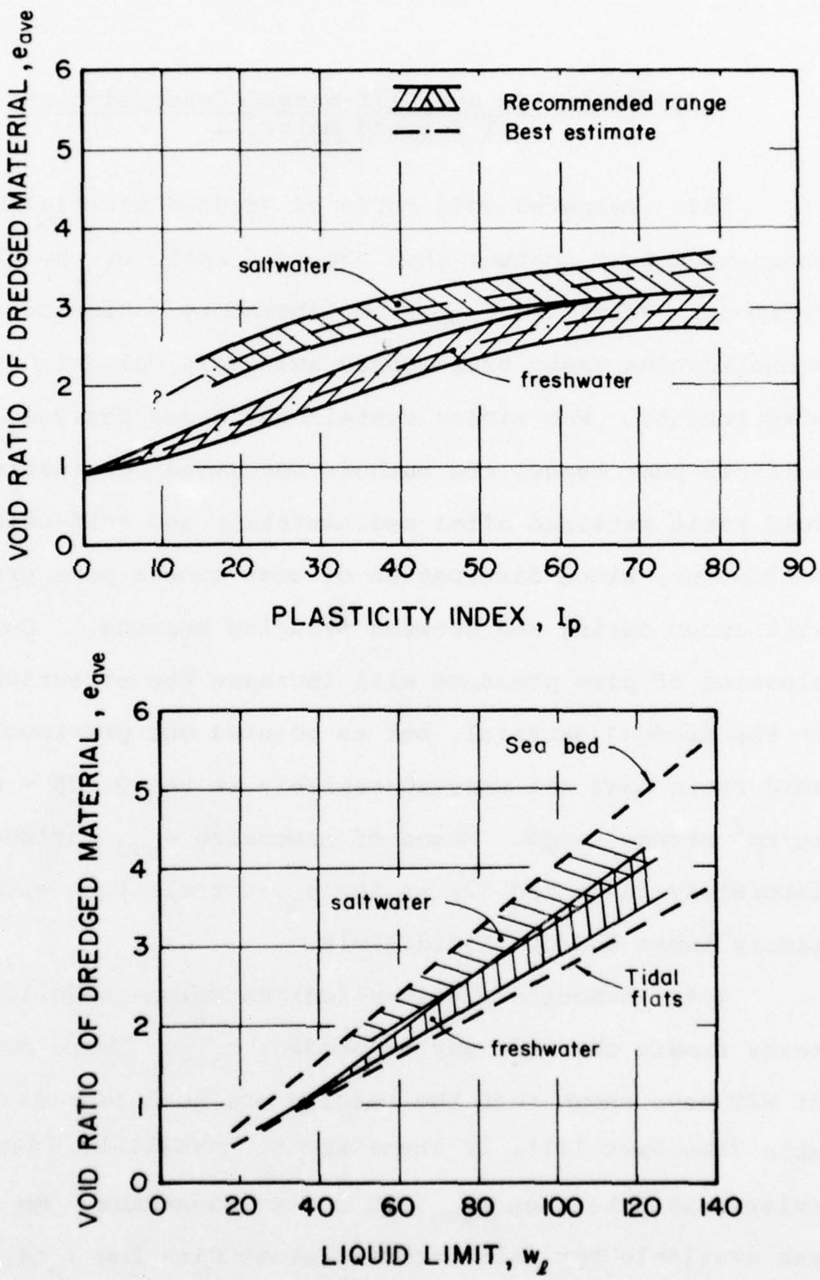

Figure 49. Void ratio and index properties of dredged material

one to calculate the volume increase* of the channel sediment after dredging, transport, and disposal. Figure 50 shows the volume increase as a function of I_p for freshwater and saltwater deposits. A volume increase factor of 1.00 indicates no volume change. Volume increases computed from the field data presented appear as data points in the figure. The scatter emphasizes the need for additional field measurements (see reference 24 for a summary of the data).

Reliability of Sizing Method

137. Table 15 summarizes the uncertainties associated with each methodology parameter used for predicting the necessary volume to contain the material removed in 1975 and disposed in area no. 12 in Cleveland Harbor. No uncertainty was associated with the volume of material to be dredged, V_t, since soundings before the job determined more or less accurately the volume removed. If the user of the sizing method believes that V_t is not reliable in his particular problem, the range of probable values can easily be incorporated in the analysis.

138. The uncertainty associated with void ratios of channel sediment and dredged material depends on the type of material and will vary for each job. However, the 20 percent variations observed in Cleveland Harbor and Branford Harbor

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* Defined as $\dfrac{1 + e_{ave}}{1 + e_o} - 1.00$

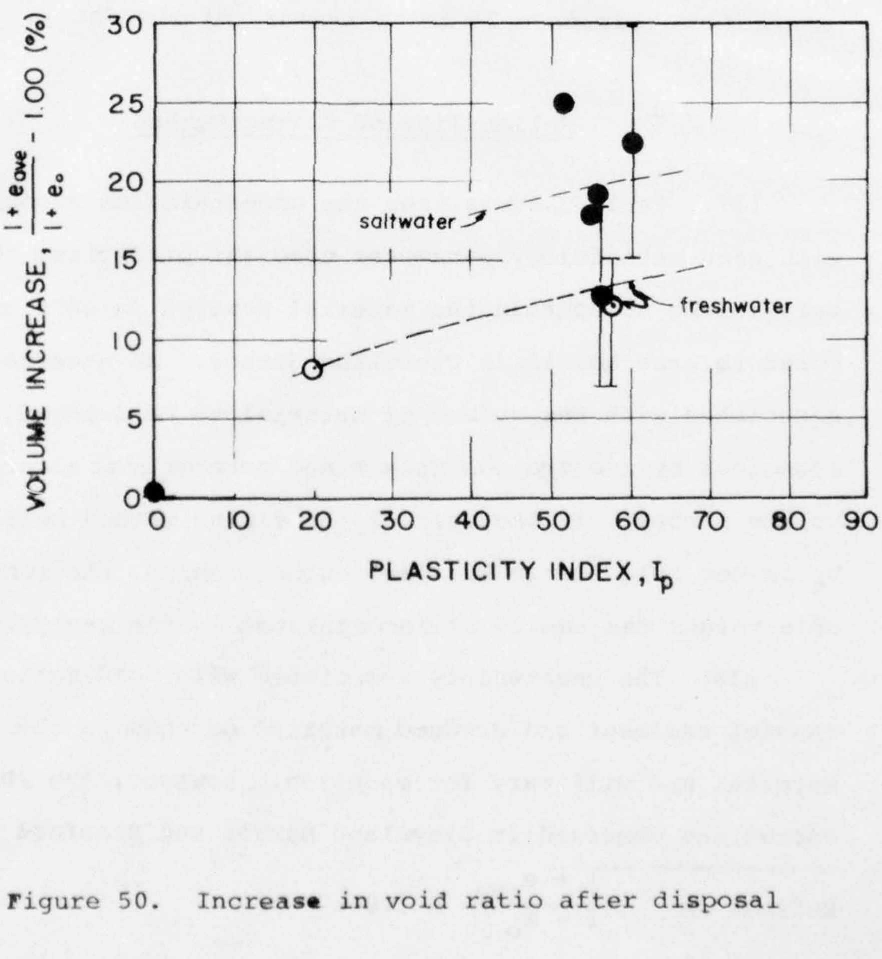

Figure 50. Increase in void ratio after disposal

Table 15

Reliability of Sizing Methodology

Parameter*	Probable Variation	Predicted Best Estimate**	Containment Volume, m^3	
			Minimum[+]	Maximum[+]
Void ratio of channel sediment, e_o	$\pm$ 20%		673,125	882,205
Void ratio of dredged material, e_{ave}	$\pm$ 15%	763,615	683,780	843,445
Efficiency factors, $F_eF_pF_c$	$\pm$ 6%		714,870	817,410

*No uncertainty associated with V_t nor F_o: volume dredged was calculated fairly accurately from surveys.

**1. $e_o = 2.05$, $e_{ave} = 2.30$, $F_eF_pF_c = 0.95$.
2. Measured containment volume = 725,590 m^3.

[+] One parameter only varies, with 2 other parameters taken as best estimates.

sediments appeared fairly typical. Based on the scatter in Figure 49, the authors selected an uncertainty of ± 15 percent for the void ratio of dredged material in Cleveland Harbor. The influence of the loss factor was relatively small ($F_e F_p F_c = 0.95$).

139. Table 15 lists the containment volumes for the expected ranges of variation of each parameter and indicates that the most important variations were due to the uncertainties in void ratios. Figure 51 illustrates the effect of each parameter on the predicted containment volume, while maintaining the others at their best estimate values. The relative error with respect to the actual measured volume is also shown. Using extreme values for each parameter, the range of containment volume as predicted by the sizing methodology will differ from the numbers shown in Table 15, but the situation where simultaneously e_{ave} will be predicted with a +15 percent error and e_o with a -20 percent error is very unlikely.

140. Figure 52 illustrates the evolution of the sizing techniques for containment areas and their probable reliability. Four methods have been applied to the 1975 material disposal in Cleveland Harbor area no. 12.

a. Bulking or design factors between 0.5 to 2.3 have been used in practice. Application of the smallest design factor to the volume dredged in Cleveland Harbor yields a predicted containment area volume of 371,455 m^3. Similarly, a maximum design factor of 2.3 yields a V_{CA} of

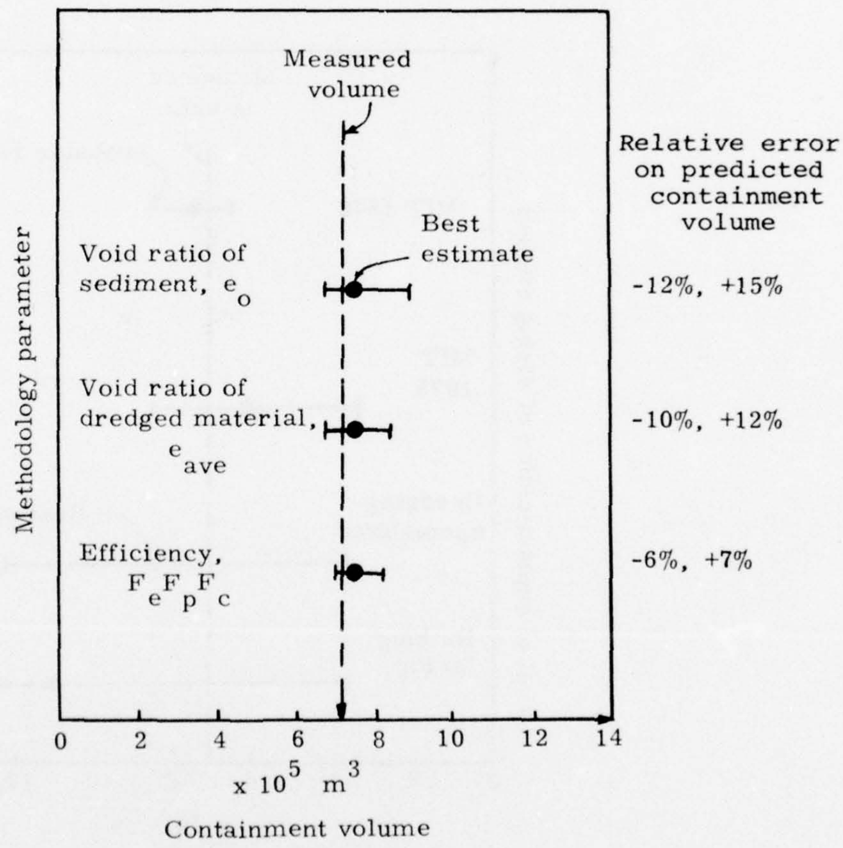

Figure 51. Effect of methodology parameters on predicted containment volumes for the 1975 disposal operation in Cleveland Harbor site no. 12

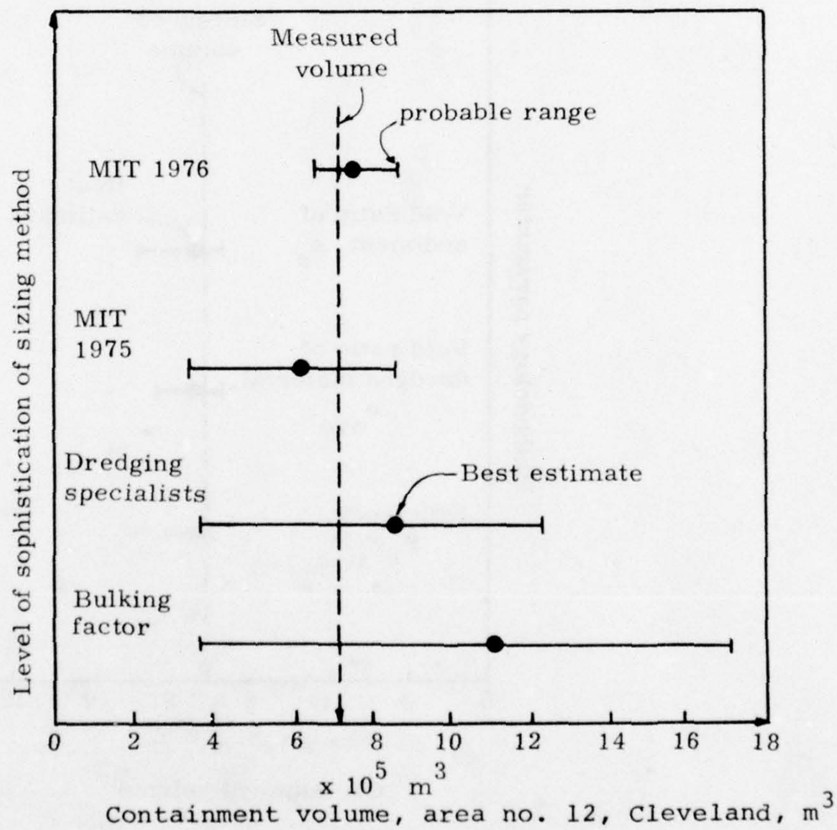

Figure 52. Reliability of sizing methods

$1,708,695\ m^3$. The best estimate prediction was obtained with the arithmetic average bulking factor.

b. The opinions from dredging specialists in the USA and Japan (see Table 1) lead to an *average sizing factor for clayey* material after sedimentation and self-weight consolidation of 1.16, with a possible range from 0.60 to 1.80. Use of these factors predicts a minimum volume of $371,455\ m^3$, a maximum of $1,337,240\ m^3$ and a best estimate of $861,775\ m^3$ (using the average sizing factor).

c. The 1975 marsh creation sizing method[3,6] predicted the following ranges of volumes:

minimum $V_{CA} = 334,310\ m^3$ ($F_eF_pF_c = 0.45$; $e_o = e_{ave}$)

maximum $V_{CA} = 882,205$ ($F_eF_pF_c = 0.95$; uncertainties on e_o and e_{ave} as in 1976 prediction)

best estimate $V_{CA} = 614,910$ ($F_eF_pF_c = 0.85$; $e_o = 2.05$; $e_{ave} = 2.30$)

d. Application of the 1976 MIT sizing method leads to a smaller variation in minimum and maximum containment volume (see Table 15). As shown in Figure 52, the authors estimate that the prediction method will yield results within a $\pm$ 15 percent range.

PART VII. CONCLUSIONS AND RECOMMENDATIONS

141. The report presented a rational method to size containment areas filled with dredged material. The technique aims at improving the bulking factor sizing method presently in use and takes into account (1) the properties of the channel sediment, (2) the behavior of the dredged material in the disposal site, and (3) the components of the dredging operation that affect volume of sediment dredged. For these purposes, the investigators surveyed current practice, reviewed pertinent variables of the dredging operation, investigated the behavior of several types of dredged material and applied the prediction methodology to four field cases.

142. The sediments and dredged material investigated (both freshwater and saltwater) came from disposal sites throughout the USA and had plasticity indices between 14 and 60. The research concentrated its effort on fine-grained materials since sands present few disposal problems. A survey of 13 dredging agencies or specialists provided more intuitive than factual estimates of the behavior of dredged material. These opinions indicate that after swelling of the material (due to the dredging process) and self-weight consolidation in the disposal area, sands occupy approximately 82 percent of their original sediment volume, silts 87 percent, and clays as much as 116 percent of their original volume. However, large variations in these factors exist.

143. Other than index characteristics, the material properties investigated in the report include:

a. Rate of settling of dredged slurry.

b. Spatial distribution of solids in containment area.

c. Excess pore pressures in dredged material.

c. Void ratio distribution of dredged material.

Void ratios of both channel sediment and dredged material were the major unknowns in the sizing technique. Other factors such as particle segregation from inflow pipe to weir or even dredging operation parameters had much less influence and involved less uncertainty when applying the sizing procedure.

144. The authors proposed a technique to predict the void ratio of dredged material from laboratory column sedimentation-consolidation tests on channel sediment. Measured versus predicted void ratios in several disposal sites agreed very well. The void ratio of the channel sediment, the rate of settling, total unit weight, and void ratio of dredged material can be related to (1) the ambient water environment, (2) the plasticity, and (3) the grain size of the material. Means for obtaining the void ratios and unit weight include undisturbed and disturbed sampling of sediment, laboratory sedimentation-consolidation tests and relationships void ratios versus index properties proposed in this report. In summary, the data presented indicate the following:

a. For slightly plastic to non-plastic fine-grained freshwater material ($I_p \leqslant 20$), the volume increase after dredging and disposal remains less than 10 percent.

b. For highly plastic saltwater material ($I_p > 50$), the volume increase after dredging and disposal can reach 30 percent.

Limited data underlie these relationships. Additional field measurements would greatly help refine selection of void ratios of sediment and dredged material.

145. The report provided the user with best estimates of the dredging operation parameters required by the methodology and the probable deviations from these best estimates. The choice of a reliable value for the overdredging factor, F_o, is the most significant, since the loss of solids during the operation was observed as very low.

146. Application of the sizing method to several actual cases proved satisfactory. In two instances, the volume was overpredicted by less than 10 percent and in a third disposal site, the prediction was unsafe by 5 percent. The containment volume required by two future dredging jobs was also computed and will hopefully be checked against actual performance upon completion of the work. In order to improve the reliability of the prediction method, one needs to:

a. Refine sampling procedures to obtain more reliable measurements of sediment void ratio.

b. Document further comparisons of predicted versus field void ratios of both channel sediment and dredged material.

c. Investigate possible means of limiting uncertainty on the overdredging factor.

147. When selecting the parameters necessary to solve the sizing equation, the authors recommend the following investigations:

a. Sampling of the sediment along length of channel.

b. Estimate of approximate consistency of sediment (penetration tests, for example).

c. Measurement of grain size and plasticity of sediment.

During the dredging operation, it is recommended to:

a. Observe dredging operation and any excessive losses.

b. After each dredging season(in a multi-year usage disposal area), verify the effective volume of dredged material and required containment volume.

148. In containment areas designed for multi-year usage, it is recommended to apply the sizing methodology at the end of each dredging year. This procedure will establish a bank of values for each methodology parameter and help reduce their uncertainty and will enable one to reexamine volume predictions and, if necessary, modify either containment volume or volume to be dredged.

149. Continued research on the containment area sizing problem should address itself to:

a. Further investigation of actual containment areas, with careful monitoring of volumes, sediment properties, dredging operation,and dredged material behavior.

b. Application of prediction methodology to more field cases in order to (1) ascertain its reliability and (2) substantiate further the relationships between void ratio and index properties developed in this report.

c. Investigation of the fundamental sedimentation-consolidation behavior of dredged

material in the laboratory, with measurement of pore pressures and solids concentration. Limited data exist but generalization of observed trends to all dredged materials needs additional research.

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APPENDIX A: FIELD SITES

Introduction

1. The Waterways Experiment Station and the Corps of Engineers District offices provided immense assistance to MIT with the seven field sites under study. This appendix describes the following containment areas in use by the Corps: Branford Harbor upland disposal site, Anacortes and Capsante, James River-Windmill Point, Browns Lake, Upper Polecat Bay, and Cleveland Harbor. Figure A1 presents a map of the USA that locates all these sites along with the Delaware disposal sites studied in Part III of the report.

Branford Harbor

2. In Branford, Connecticut, located on the northern shoreline of Long Island Sound approximately 10 miles east of New Haven (see Figure A2), channel-bottom silting creates entrance problems for boats and necessitates dredging about every 10 years. Material from previous channel dredging projects has been deposited on upland disposal sites adjacent to the harbor area. One such site is the proposed disposal area for the dredging scheduled for September 1974 (shown in Figure A2). Full site descriptions are presented in References 3 and 6.*

3. The recently deposited channel sediments consist

*References cited in the appendices are given in the List of References following the main text.

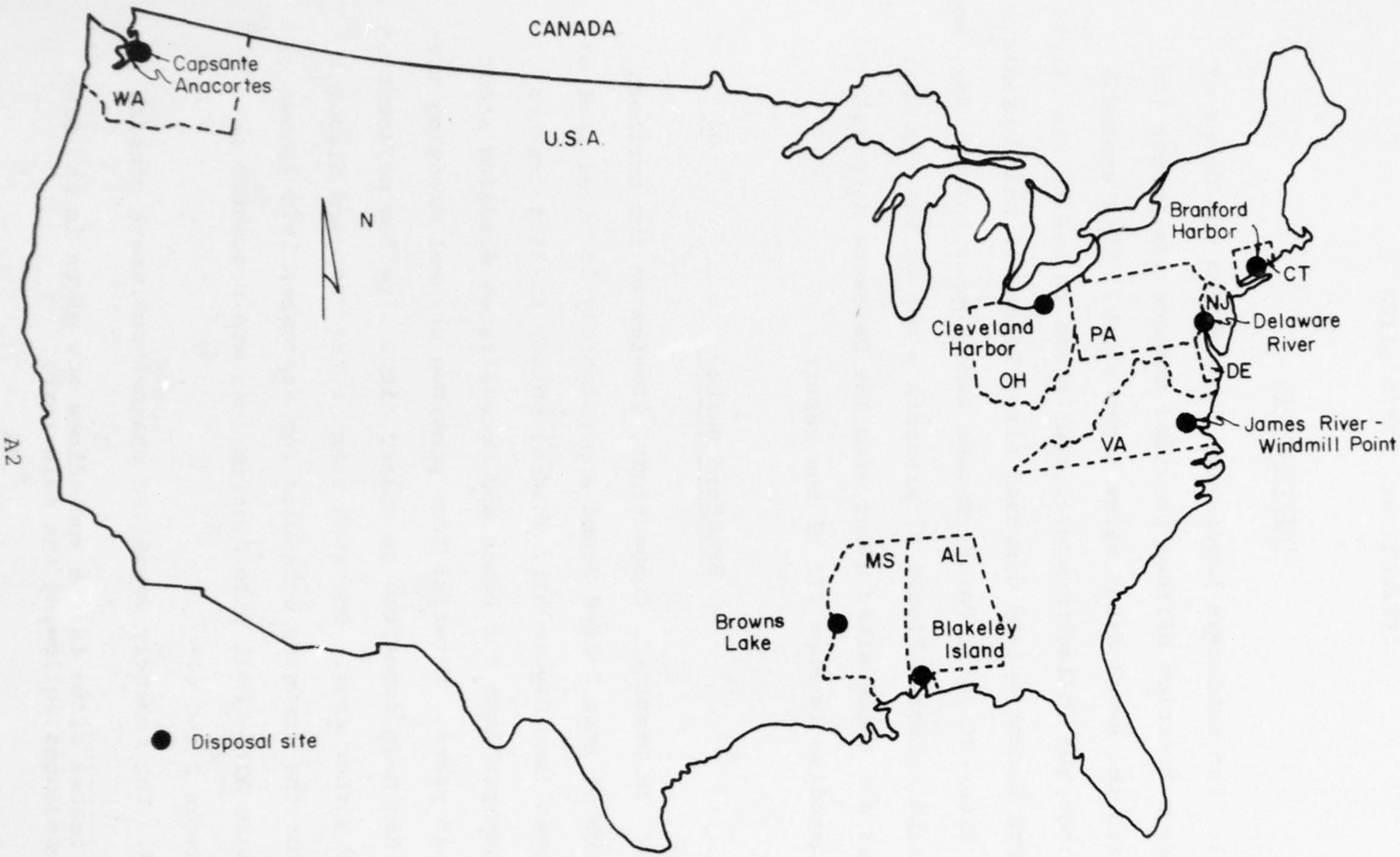

FIGURE AI. LOCATION OF FIELD SITES UNDER STUDY

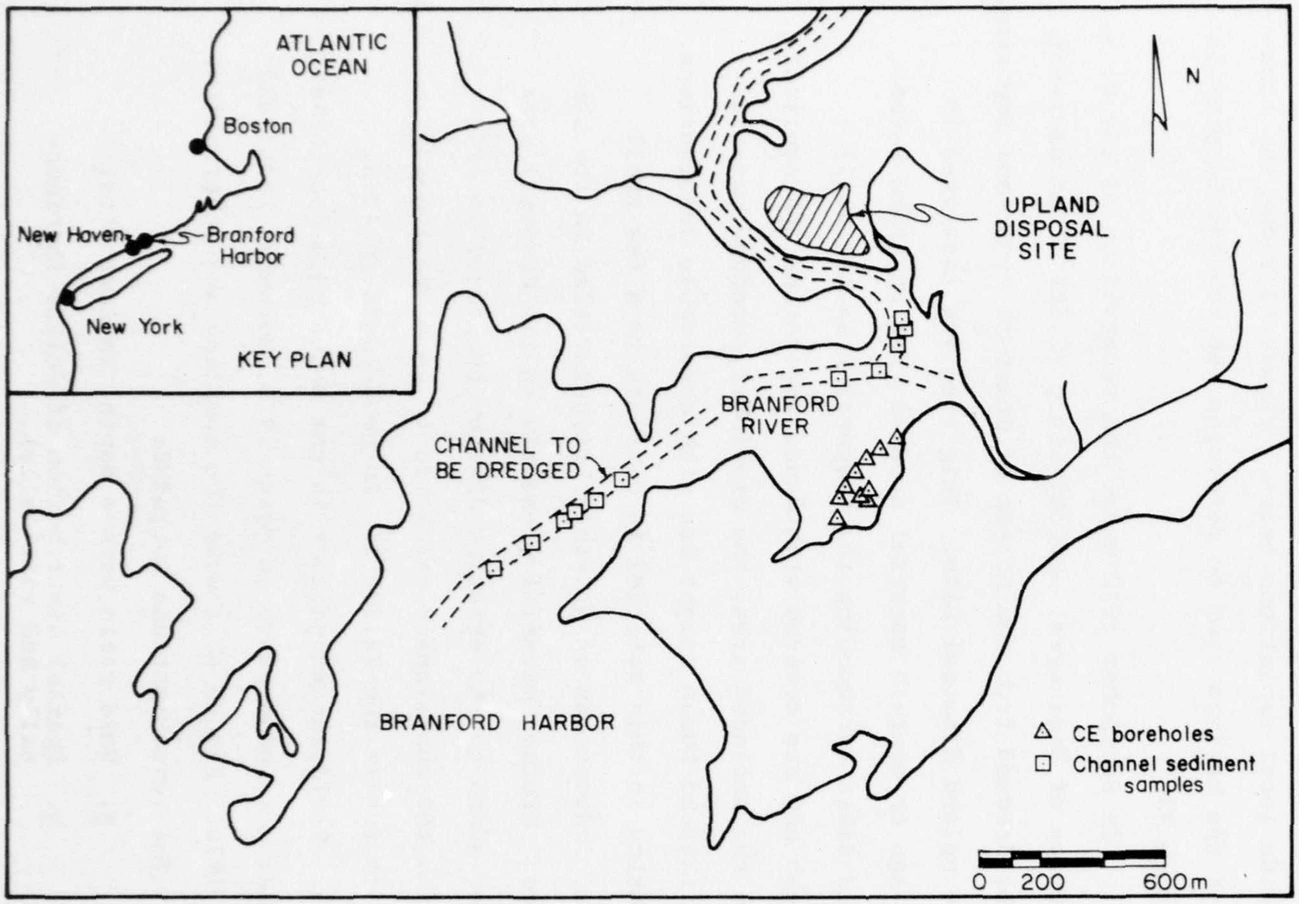

FIGURE A2. LOCATION PLAN OF BRANFORD HARBOR

of plastic organic clay. A 60- to 120-cm depth typically accumulates between maintenance dredging operations, although some wide local variations exist. Figure A2 shows the location of the borings used to determine the foundation profile in Figure 43.

4. In September 1972 under the supervision of the U. S. Army Corps of Engineers, approximately 72,500 m^3 of sediment will be dredged from the bottom of Branford River and deposited in the upland disposal site. This area was last used 10 years ago to contain material dredged from Branford Harbor. The old dikes surrounding the disposal area are still apparent and are covered with dense vegetation (phragmites). Within the enclosed area, the previously dredged material can withstand human weight but with observable deformations. Vegetation in this material is confined to a few small mounds, indications of possible irregularities in the subsurface. Dredged material presently in the disposal area will be added to the existing dike by bulldozer in order to raise the containment structure to an elevation sufficient to retain the 72,500 m^3 to be dredged in 1976.

5. Field investigations in the Branford Harbor upland disposal site took place in March 1975, November 1975, and March 1976. Figure 42 showed the sampling and observations done. The investigations included:

a. Void ratio versus depth (in test pits).

b. Spatial distribution of solids (horizontally and vertically).

c. Measurement of field unit weight.

d. Measurement of excess pore pressures in dredged material and foundation.

e. Visual observations of dike, tidal fluctuations, topography, and general layout.

f. Sampling of dredged material and foundation material.

g. Sampling of channel sediment in harbor.

6. In order to estimate the profile of the foundation immediately beneath the disposal area, three test pits were dug in the deposited dredged material. Samples were taken at various depths. These samples were then tested for index properties and compared with the material to be dredged. Table A1 lists the respective Atterberg limits: the two materials had very similar properties, with a liquid limit of 95 and a plastic limit of 54. All tests by MIT were done according to Lambe.[25] In the Branford Harbor Disposal site, because no borings were available below the dredged material and peat, the profile was assumed indentical to the foundation underlying the harbor.

Anacortes

7. The Anacortes disposal site, 130 km north of Seattle, Washington, and three km south of the Capsante disposal site (see location map, Figure A3) contains material dredged in 1975 from the nearby Anacortes navigation and berthing channels, in Fidalgo Bay.

Table A1

Index Properties of Branford Harbor Materials

Material	Liquid Limit w_l	Plastic Limit w_p	Plasticity Index I_p	Specific Gravity of Solids G_s	Remarks
Channel Sediment (1975)	97.7 (51.0-140.0)	47.1 (32.5-61.0)	50.6 (28.0-95.0)	2.66 (2.61-2.72)	10-15 tests
Dredged Material in Upland Disposal Site	91.8 (74.0-102.0)	35.3 (34.1-36.7)	56.5 (39.2-65.4)	2.66	6 tests
Average	94.8	41.2	53.6	2.66	

*From Corps of Engineers' Information and References 3 and 6.

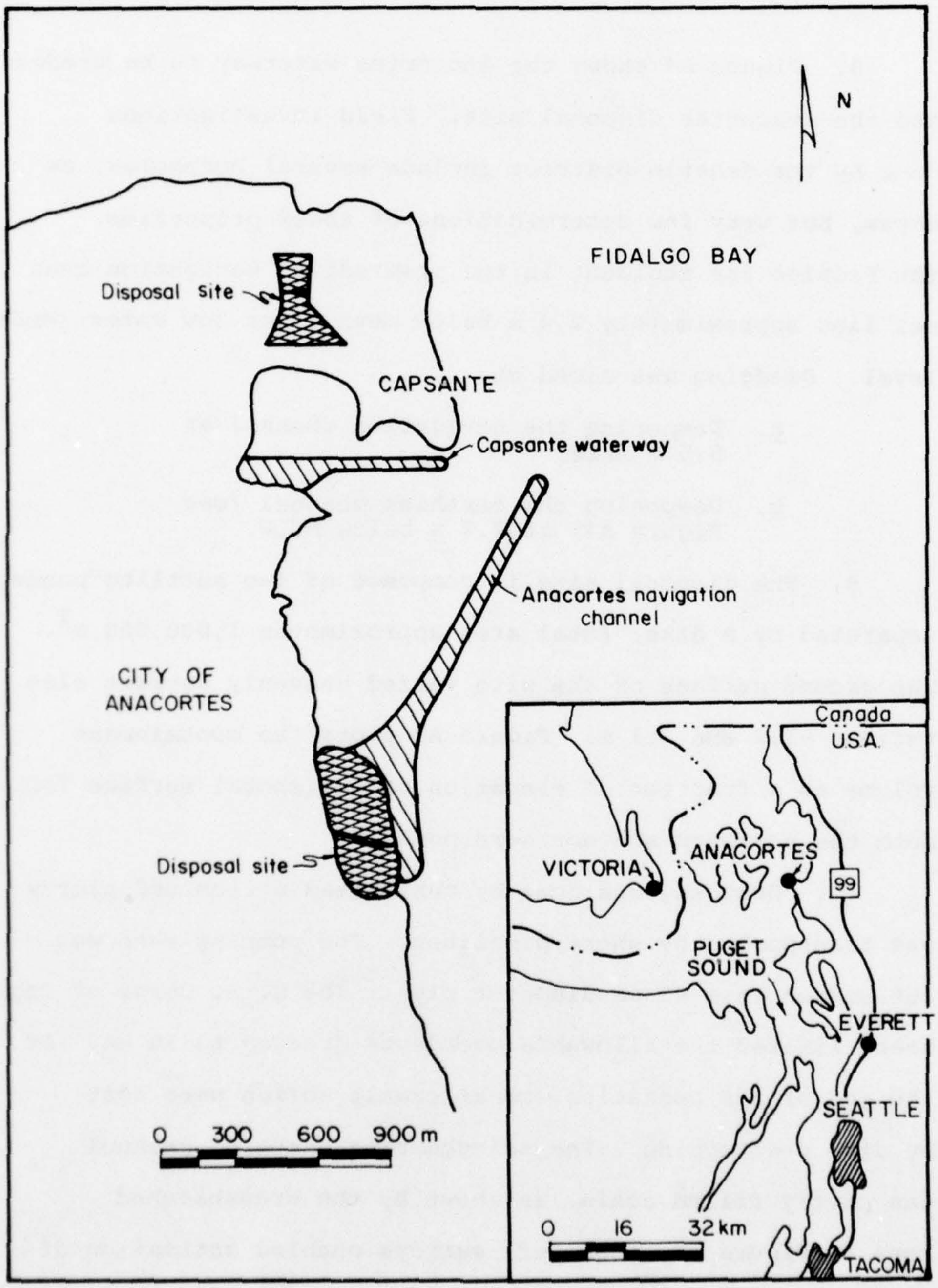

FIGURE A3. LOCATION MAP OF ANACORTES AND CAPSANTE SITES

8. Figure A4 shows the Anacortes waterway to be dredged and the Anacortes disposal site. Field investigations done by the Seattle District include several boreholes, as shown, but very few determinations of index properties. The Fidalgo Bay sediment in the predredging navigation channel lies approximately 2.4 m below mean lower low water (MLLW) level. Dredging was aimed at:

- a. Deepening the navigation channel at 5.5 m MLLW.
- b. Deepening the berthing channel (see Figure A4) at 7.3 m below MLLW.

9. The disposal site is composed of two settling ponds separated by a dike; total area approximates 1,000,000 m^2. The ground surface of the site varied unevenly between elevations -1.2 and 3.1 m. Figure A5 plots the containment volume as a function of elevation of horizontal surface for both the southern and northern ponds.

10. Dredging was done by cutterhead action and slurry was transported by short pipelines. The pumping rate was 460 cm/sec in a 45-cm diameter pipe. The U. S. Corps of Engineers limited the allowable overdepth dredged to 30 cm. At the end of the operation, considerable solids were lost by dike overtopping. The neighbouring berthing channel was partly filled again, as shown by the crosshatched zone in Figure A4. However, surveys enabled estimation of the volume of material lost. The total volume of sediment removed (as paid to the contractor) was 404,230 m^3, and

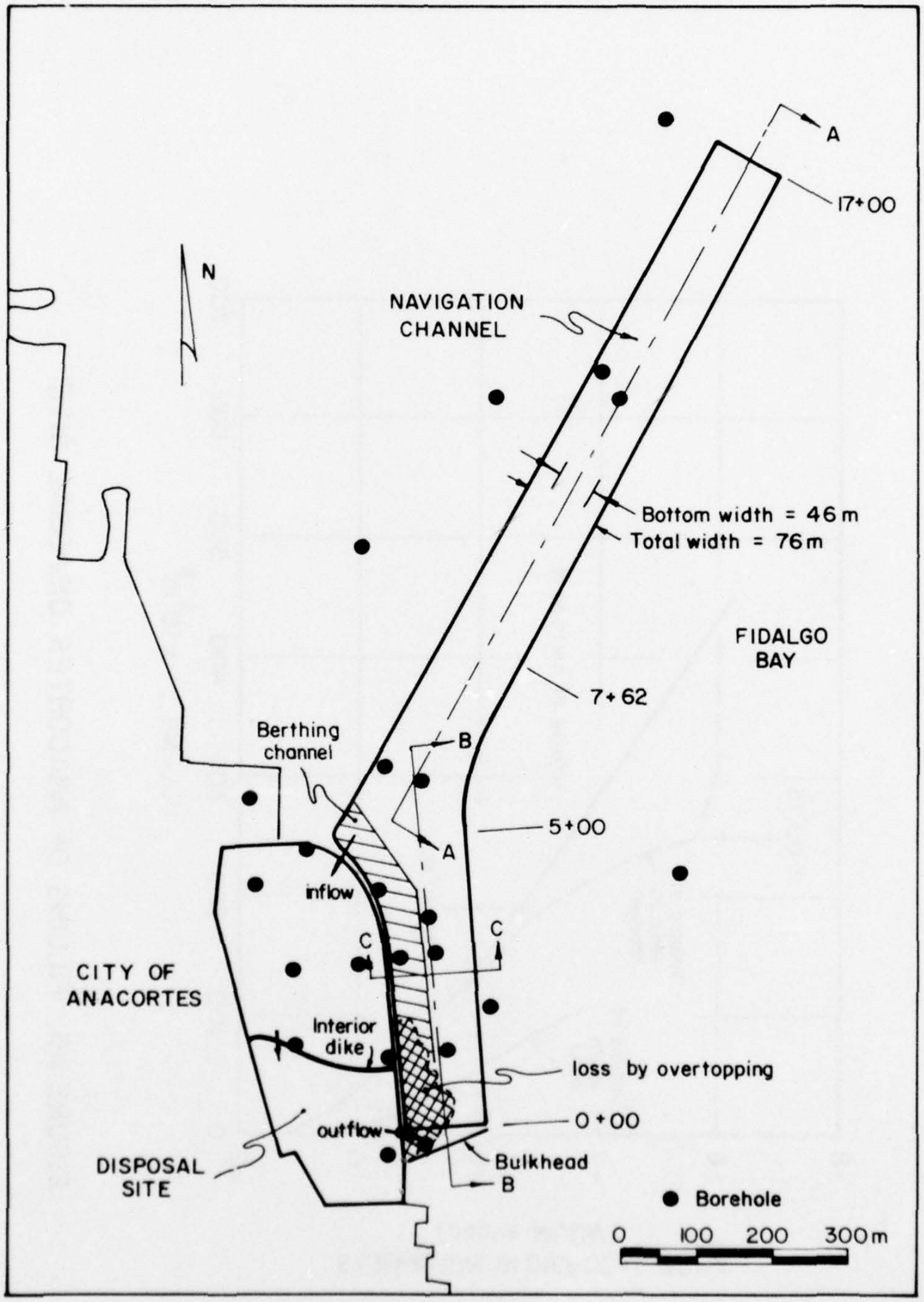

FIGURE A4. 1975 ANACORTES DISPOSAL SITE AND NAVIGATION CHANNEL

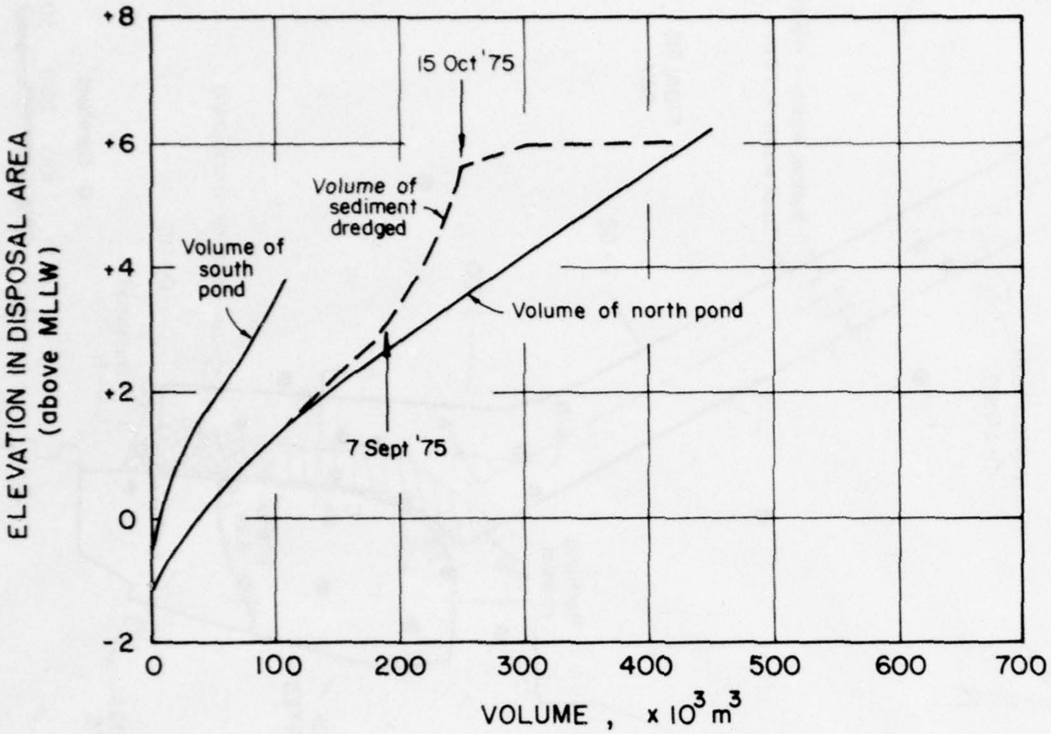

FIGURE A5. FILLING OF ANACORTES DISPOSAL SITE

20,475 m^3 were lost in the berthing. (Effectively a volume of 27,300 m^3 was computed from the surveys available, but allowances were made for a possible 25 percent swell from sediment conditions).

11. Figures A6 and A7 plot the profiles along three cross sections of the channel dredged. Between Stations 0 + 00 and 6 + 00*, a stiff plastic clay sediment (CH) was predominant; whereas, between Stations 6 + 00 and 17 + 00, a softer silt (ML) was encountered. Based on the soil profiles from the 23 boreholes available in the channels, the relative proportions of each material was computed.

12. Figure A5 plots the volume of dredged material in the area versus the elevation of the area. Between August 21 and September 7, 1975, the northern part of the channel was dredged and the dredged material showed limited swell.** However, from September 7, 1975, until December, 1975, the material between Stations 0 + 00 and 6 + 00 was dredged and deposited in the site, and the dredged material curve diverged rapidly from the disposal area volume curve. This was due to the different sediment materials encountered in the two sections of the channel. Until September 7, mostly silts were dredged; whereas afterwards, clays were predominant. However, by October 15, overtopping occurred and the

*In meters.

**If the dredged material curve follows exactly the containment volume curve, no swell occurs (i.e., $1 + e_{ave} = 1 + e_o$).

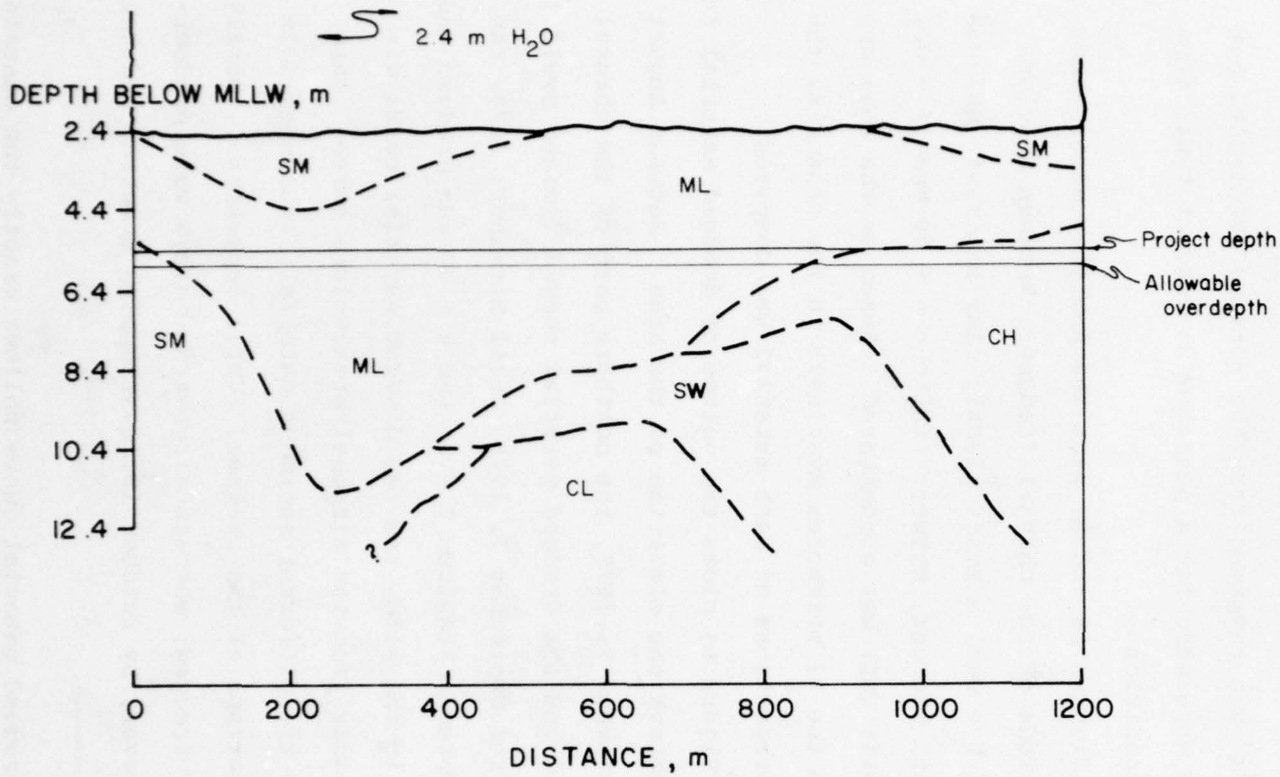

FIGURE A6. PROFILE ALONG CROSS SECTION A-A OF ANACORTES CHANNEL

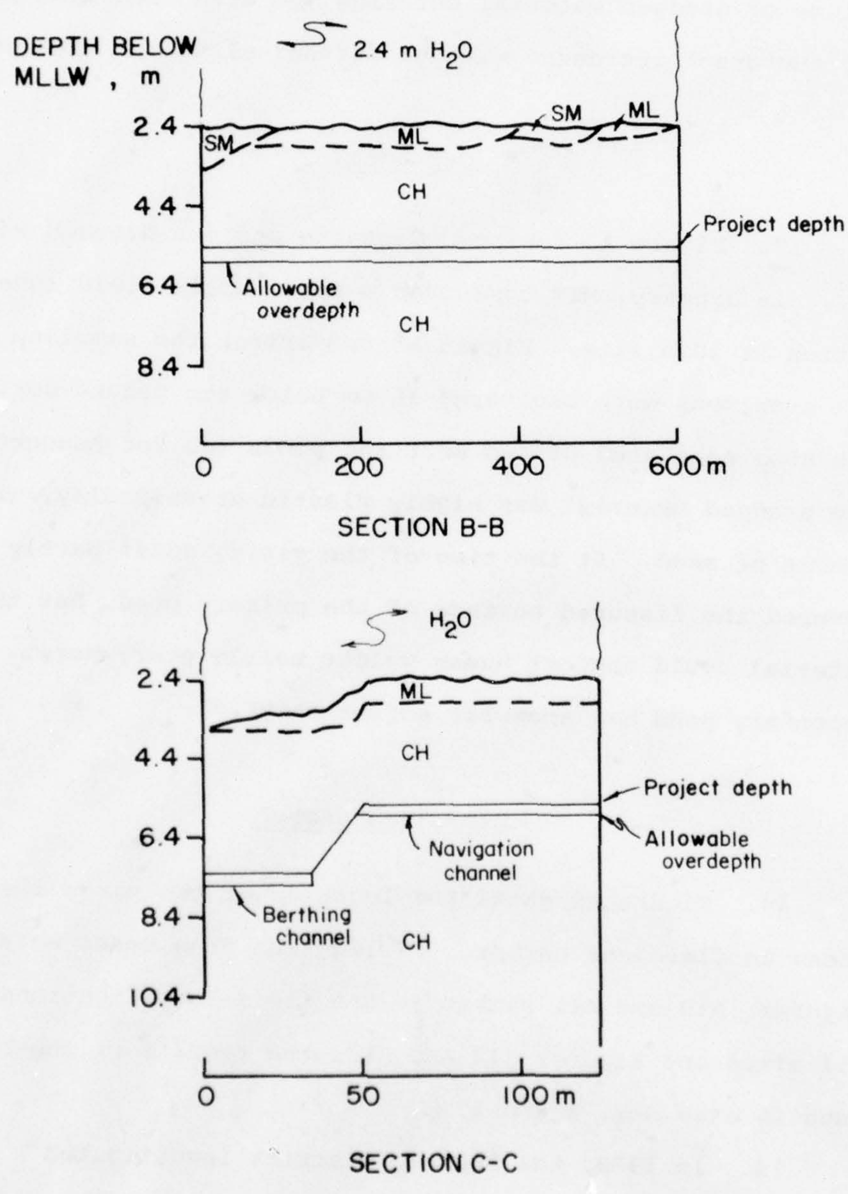

FIGURE A7. PROFILES ALONG CROSS SECTIONS B-B AND C-C OF ANACORTES CHANNEL

volume of dredged material entering the area (and also exiting the area) increased without further elevation increase.

Capsante

13. Figure A3 depicted Capsante and its dredged waterway. In January, MIT conducted a small scale field investigation at this site. Figure A8 summarizes the sampling done. All specimens were recovered 15 cm below the ground surface. The area consisted of two settling ponds (as for Anacortes). The dredged material was highly plastic organic clay, with traces of sand. At the time of the visit, water partly covered the fissured surface of the primary pond, but the material could support human weight nearly everywhere. The secondary pond had somewhat softer material.

Cleveland Harbor

14. Figure A9 shows the location of the three disposal areas in Cleveland Harbor. Filling was done under water. Figures A10 and A11 summarize the field investigations at all sites and Figures A12 and A13, the results of the borings in area nos. 1 and 2.

15. In 1972, the Buffalo District investigated area nos. 1 and 2. MIT investigated area no. 12 in December 1975 and March 1976. The study at area no. 12 included the following measurements and observations:

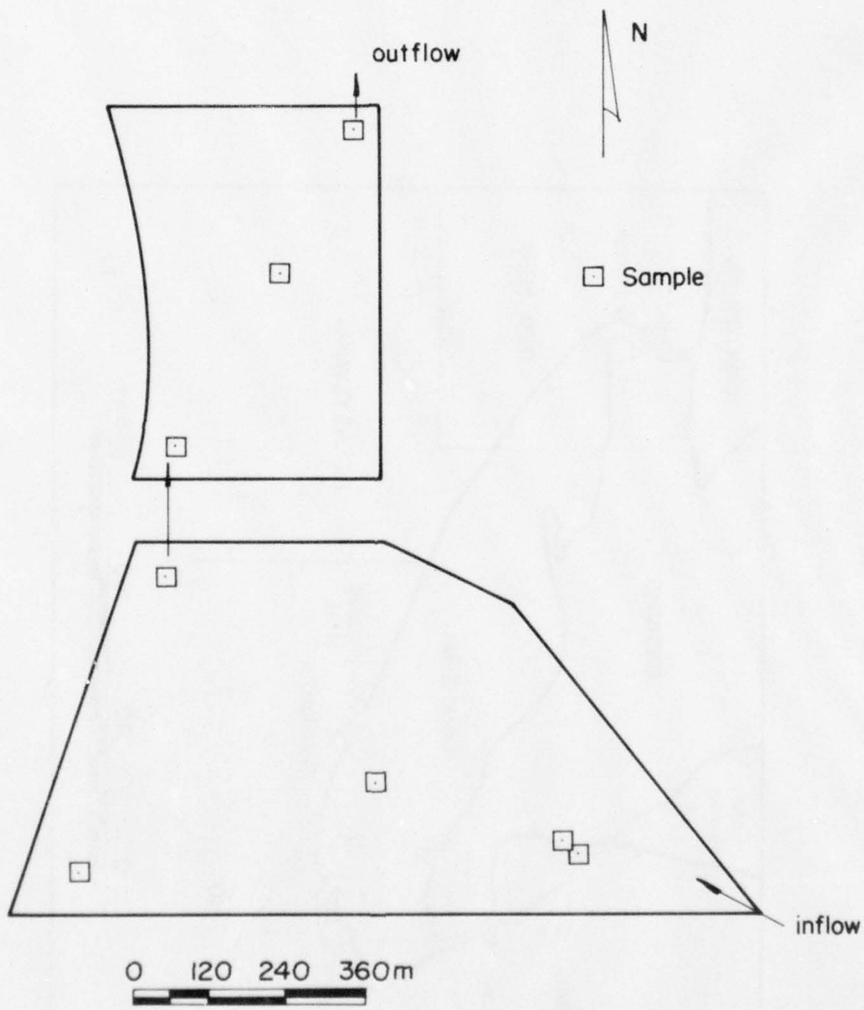

FIGURE A8. CAPSANTE DISPOSAL SITE

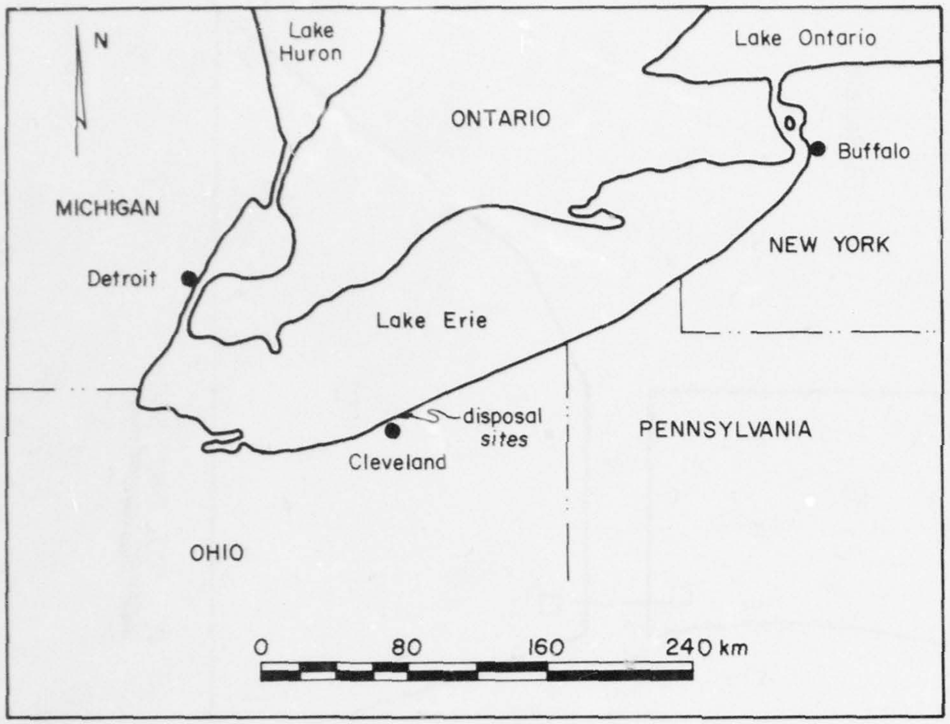

FIGURE A9. LOCATION MAP OF CLEVELAND HARBOR DISPOSAL SITES

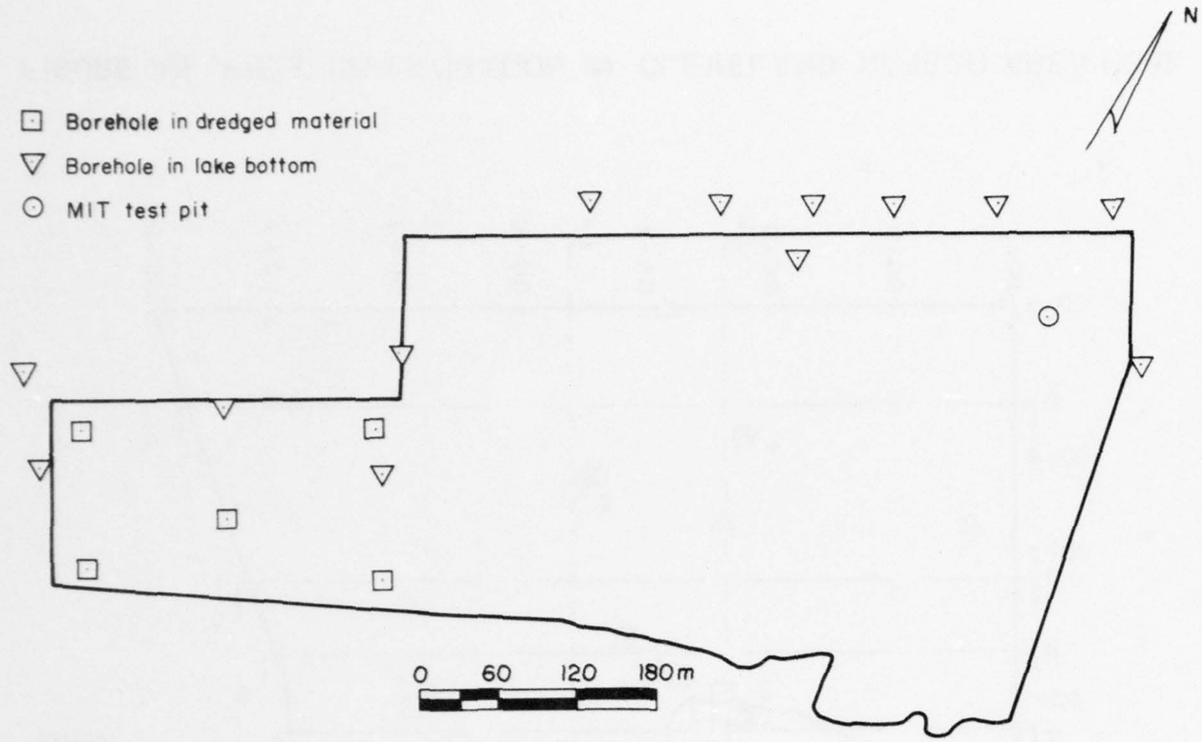

FIGURE A10. FIELD INVESTIGATION IN CLEVELAND HARBOR AREA NOS. 1 & 2

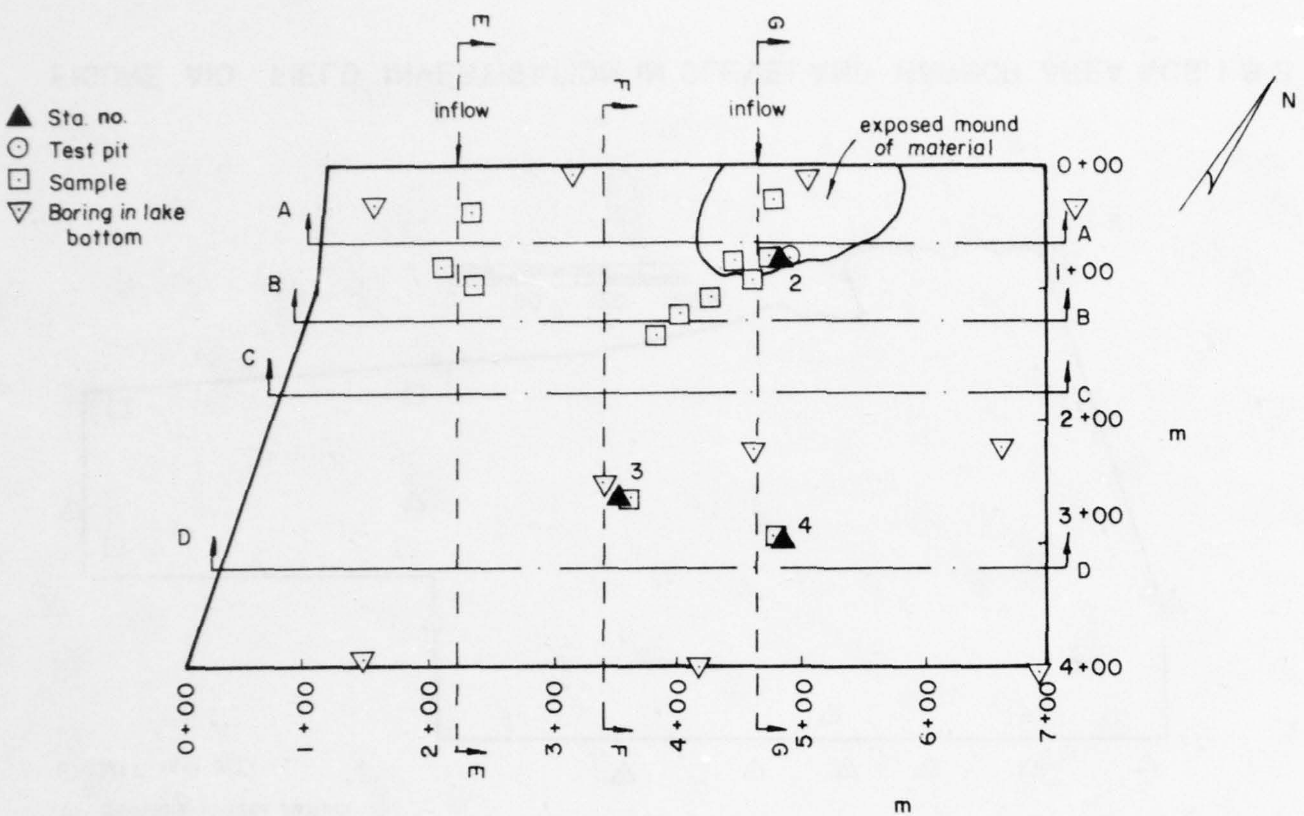

FIGURE A11. FIELD INVESTIGATION IN CLEVELAND HARBOR AREA NO. 12

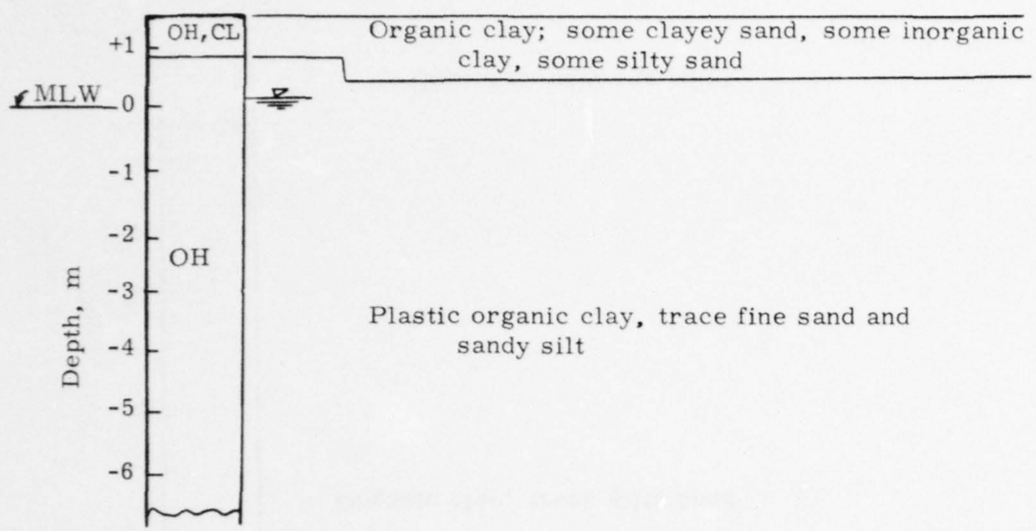

Figure A12. Description of dredged material in area no. 1.

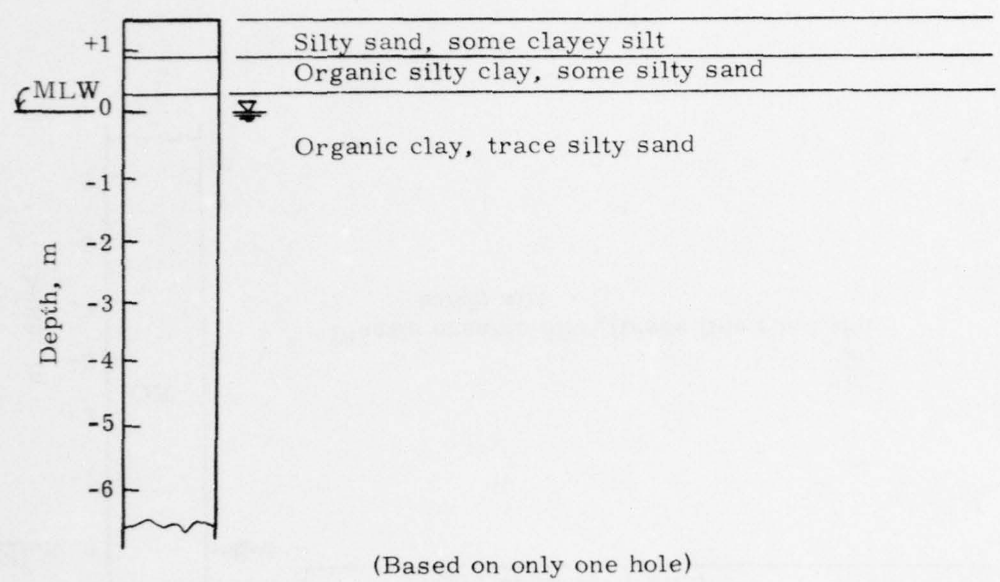

Figure A13. Description of dredged material in area no. 2.

a. Water conductivity and pH of field water.

b. Spatial distribution of solids.

c. Grain-size distribution versus depth.

d. Excess pore pressures in the newly dredged material.

e. Sampling of hopper material and dredged material inflowing in area.

f. Solids concentration at various locations.

g. Inspection of dredging operation.

h. Observation of containment structure.

16. Figures A14 and A15 plot the profile of the dredged material deposited in area no. 12 between April and December 1975. Measurements of the lake bottom date from April 1974; measurements of the dredged material interface was done in early 1976. Cross section identifications refer to those shown in Figure A11.

James River-Windmill Point

17. The Windmill Point disposal area, on the James River in Virginia, is located about two-thirds of the way from Norfolk to Richmond (see Figure A16). Open-water dumping of dredged material from biannual maintenance of the navigation channel in James River created a small island in the middle of a wide shoal,[3,11] where dredged material was deposited in 1974.

18. Field investigations done by MIT determined index

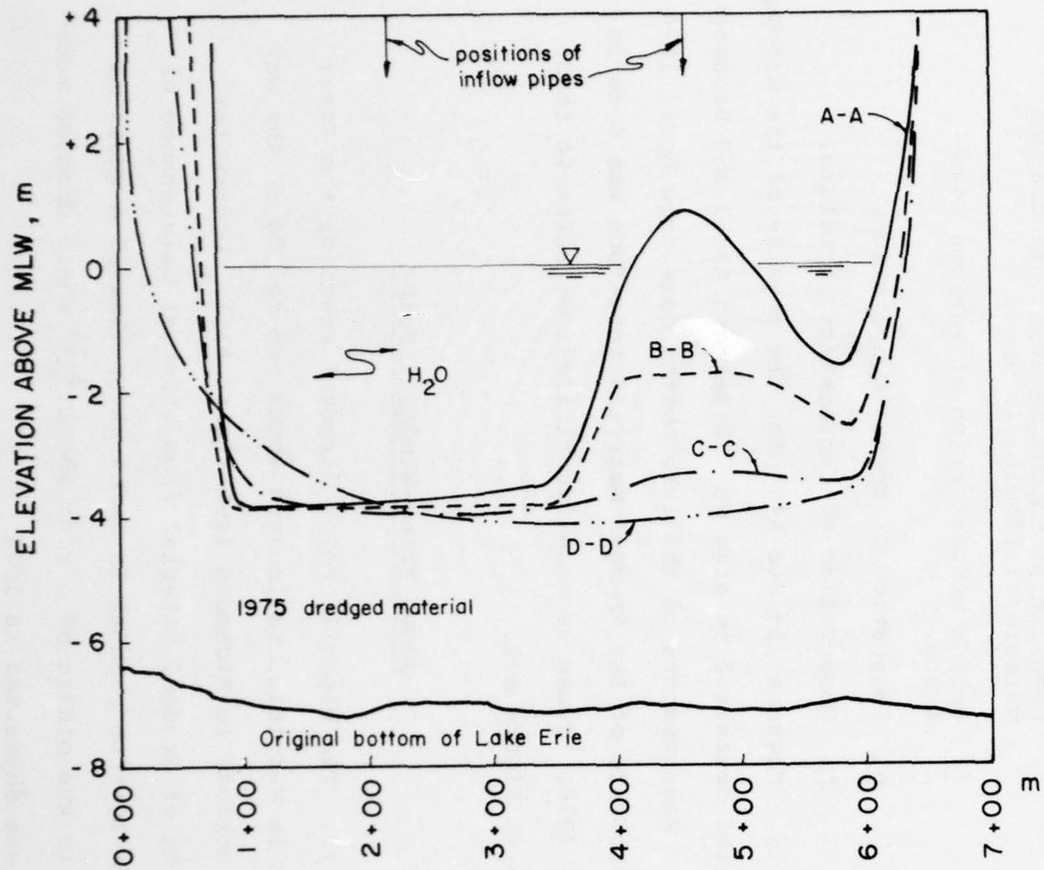

FIGURE A14. DREDGED MATERIAL DEPOSITED IN 1975 IN AREA NO. 12 (EAST-WEST CROSS SECTIONS)

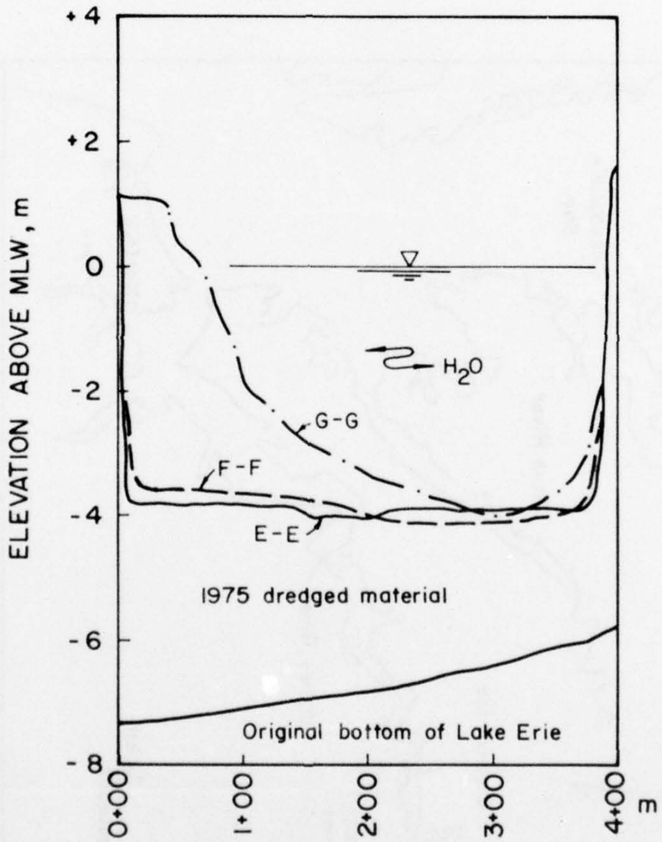

FIGURE A15. DREDGED MATERIAL DEPOSITED IN 1975 IN AREA NO. 12 (NORTH-SOUTH CROSS SECTIONS)

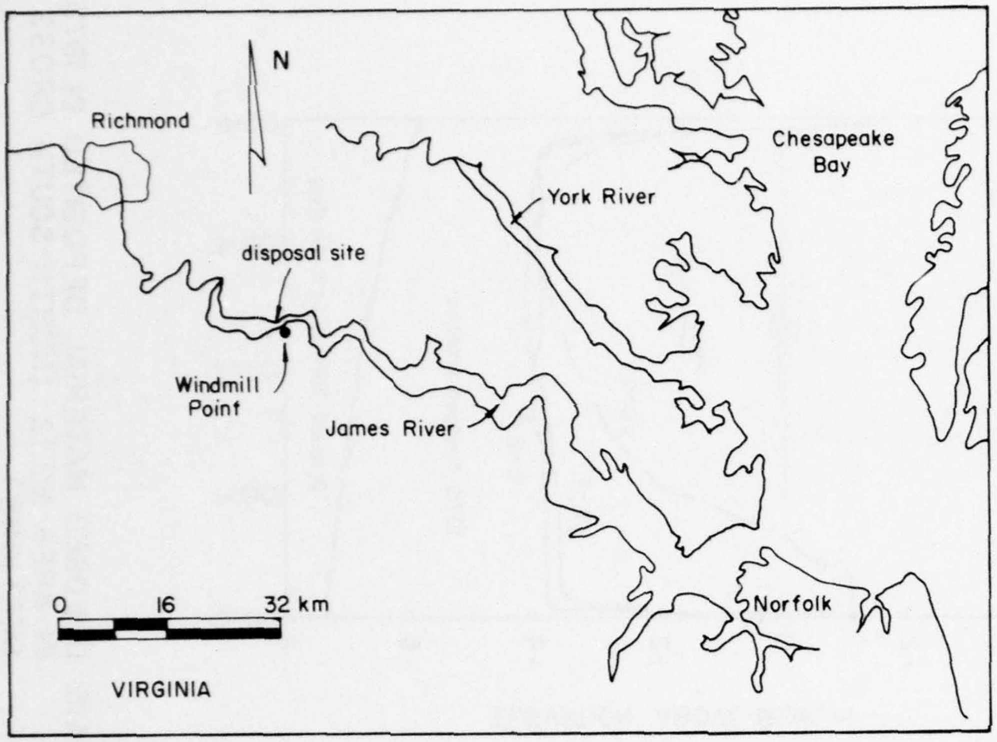

FIGURE A16. LOCATION MAP OF JAMES RIVER - WINDMILL POINT DISPOSAL SITE

properties of the dredged material and the spatial distribution of solids. Sedimentation and consolidation characteristics were studied in the laboratory. Water contents of both sediment and dredged material and field vane undrained strengths of the dredged material were measured in 10 holes by Old Dominion University. Water contents in sandy sediment averaged 1.40. On the other hand, water content in more plastic sediment, measured by Soil and Materials Engineers, Inc., averaged 2.12.

Browns Lake

19. Browns Lake, also called WES Lake, is located on the government reservation of the Waterways Experiment Station (WES) in Vicksburg, Mississippi. Dredging took place between March 23 and April 16, 1976. During and after the operation, WES conducted a special field investigation with measurements of:

- a. Water contents with depth.
- b. Grain sizes with depth.
- c. Spatial distribution of solids.
- d. Index properties of dredged material.

No information on the channel sediment was available. Figure A17 identifies the sampling holes in the area and Figures A18 and A22 plot void ratio versus depth versus time measurements in the 5 zones predefined in Part III.

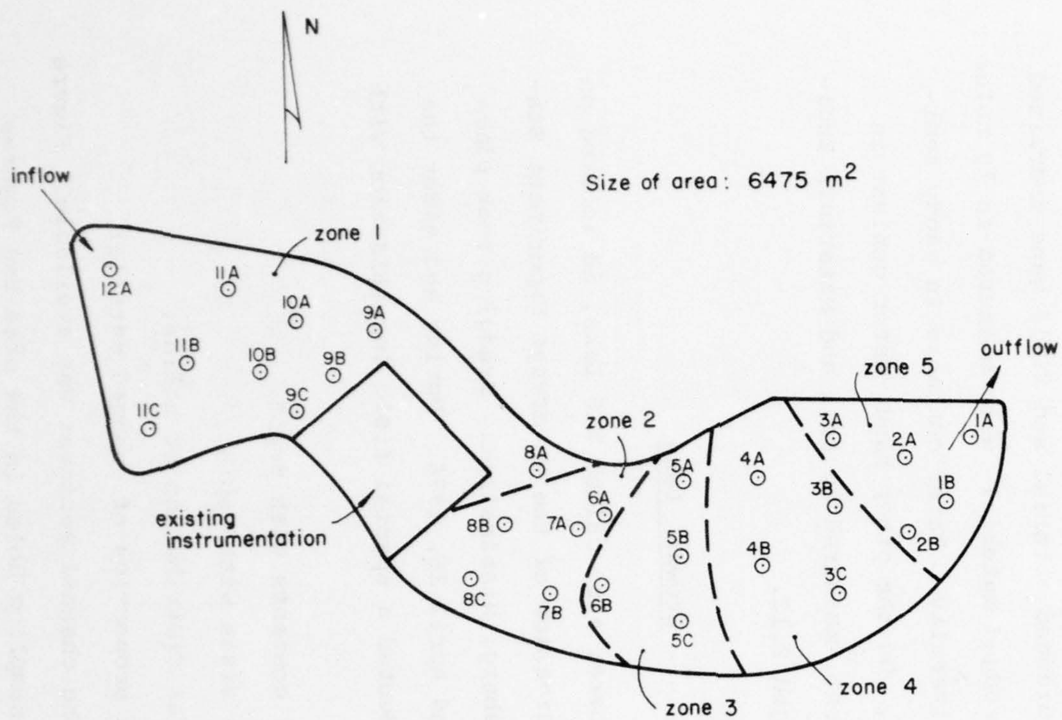

FIGURE A17 INVESTIGATION AT BROWNS LAKE DISPOSAL SITE

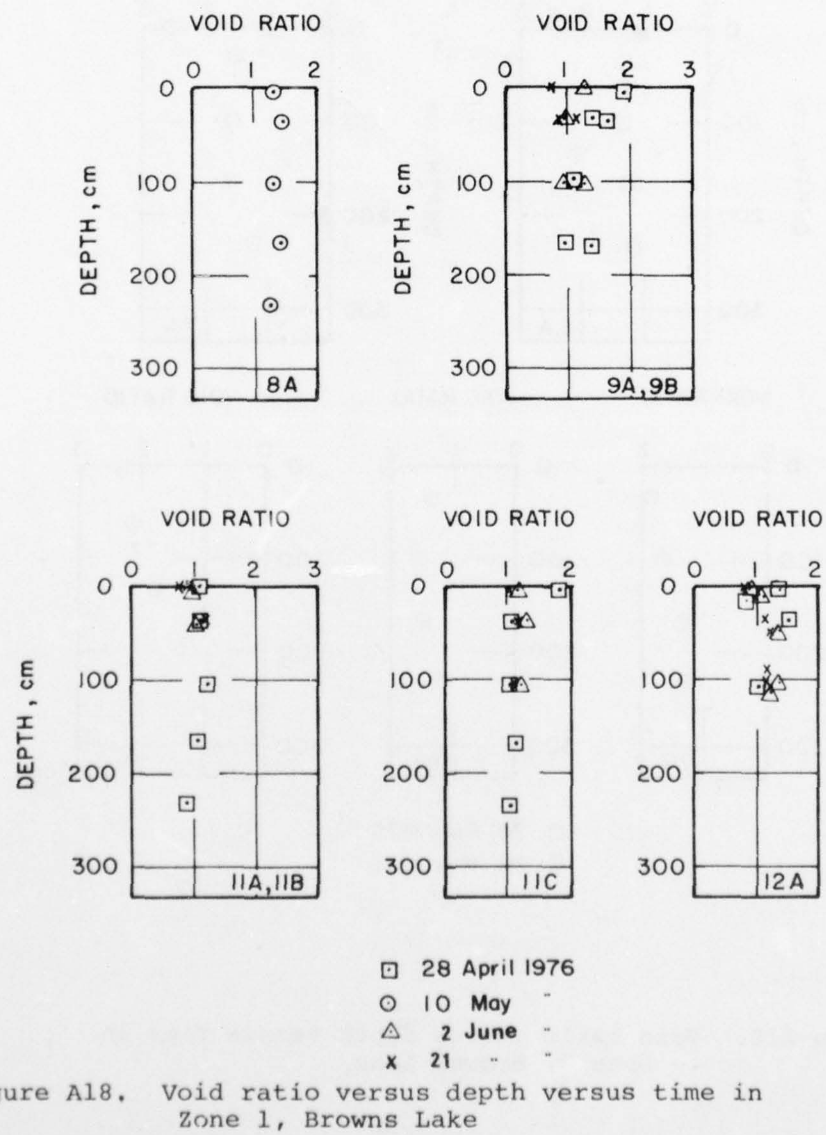

Figure A18. Void ratio versus depth versus time in Zone 1, Browns Lake

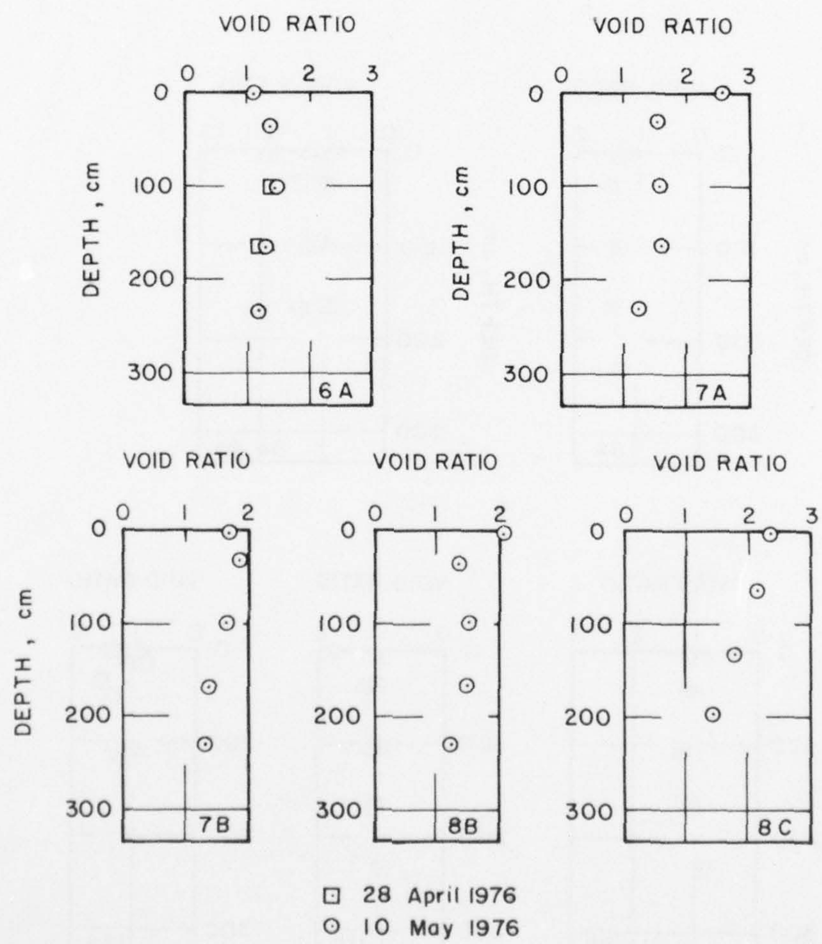

Figure A19. Void ratio versus depth versus time in Zone 2, Browns Lake

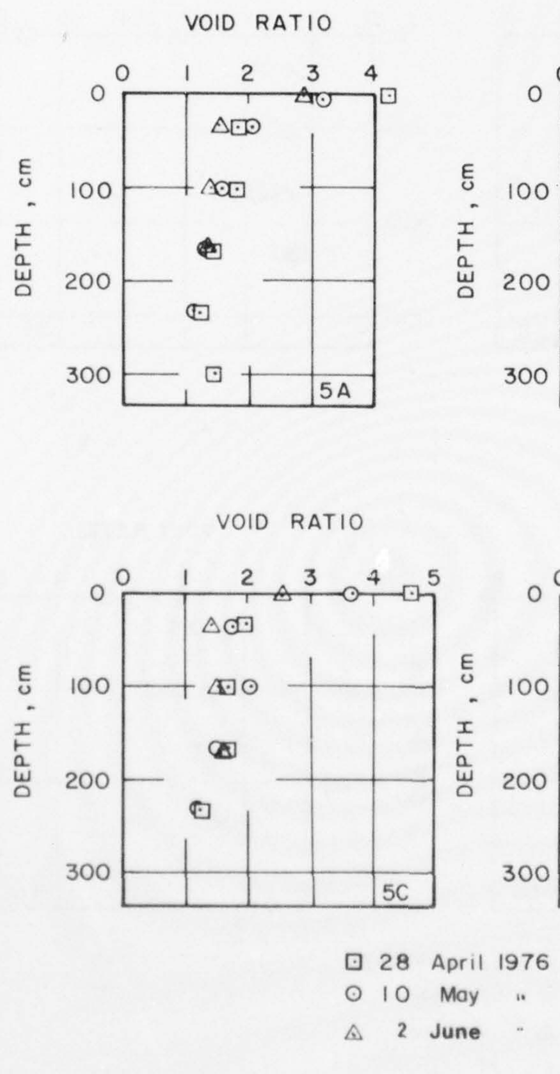

Figure A20. Void ratio versus depth versus time in Zone 3, Browns Lake

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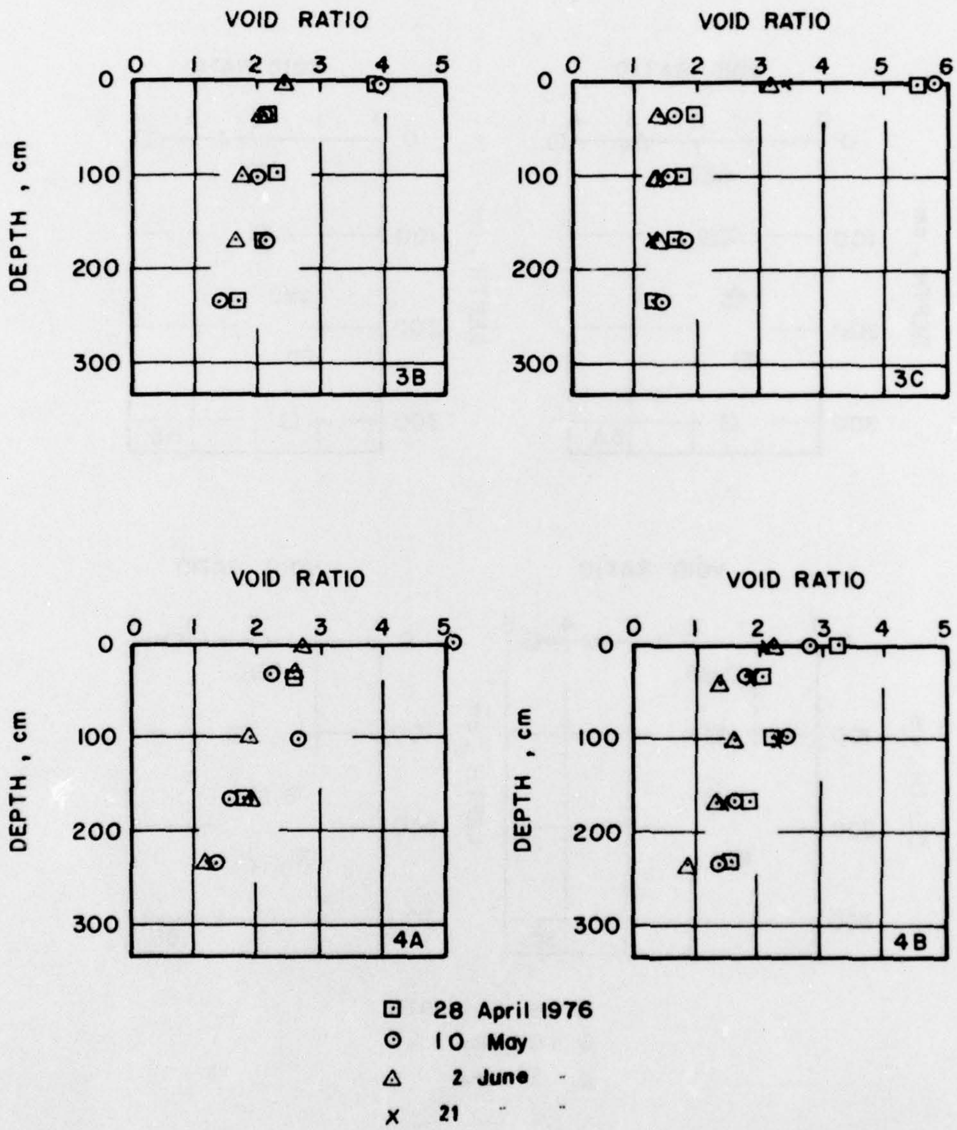

Figure A21. Void ratio versus depth versus time in Zone 4, Browns Lake

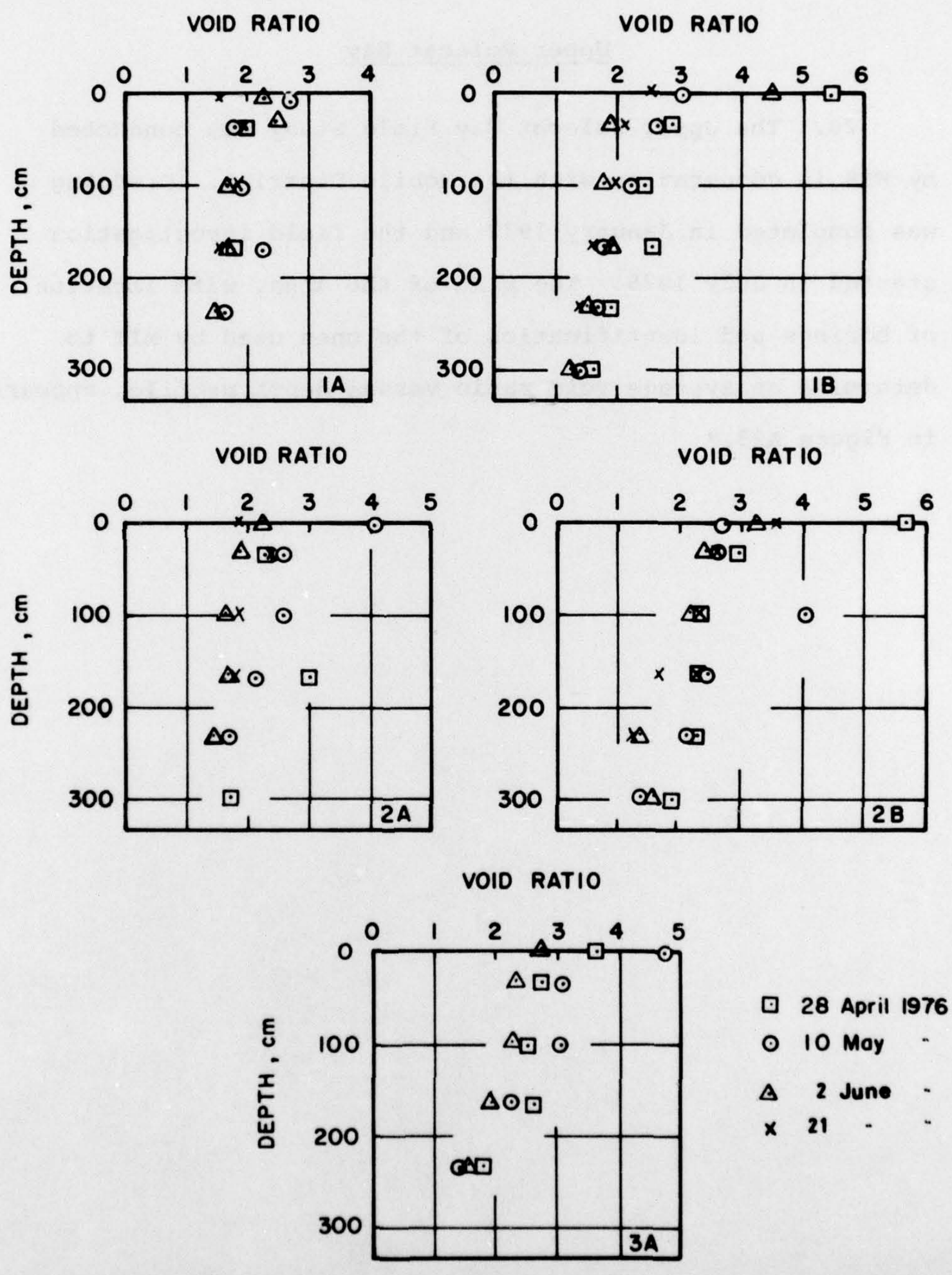

Figure A22. Void ratio versus depth versus time in Zone 5, Browns Lake

Upper Polecat Bay

20. The Upper Polecat Bay Field Study was conducted by WES in cooperation with the Mobile District. Dredging was completed in January 1973 and the field investigation started in July 1975. The plan of the area, with location of borings and identification of the ones used by MIT to determine an average void ratio versus depth profile, appears in Figure A23.*

*Further details on this site and the densification study carried out at the Upper Polecat Bay disposal site since July 1975 should be available in the report of this particular DMRP research project.

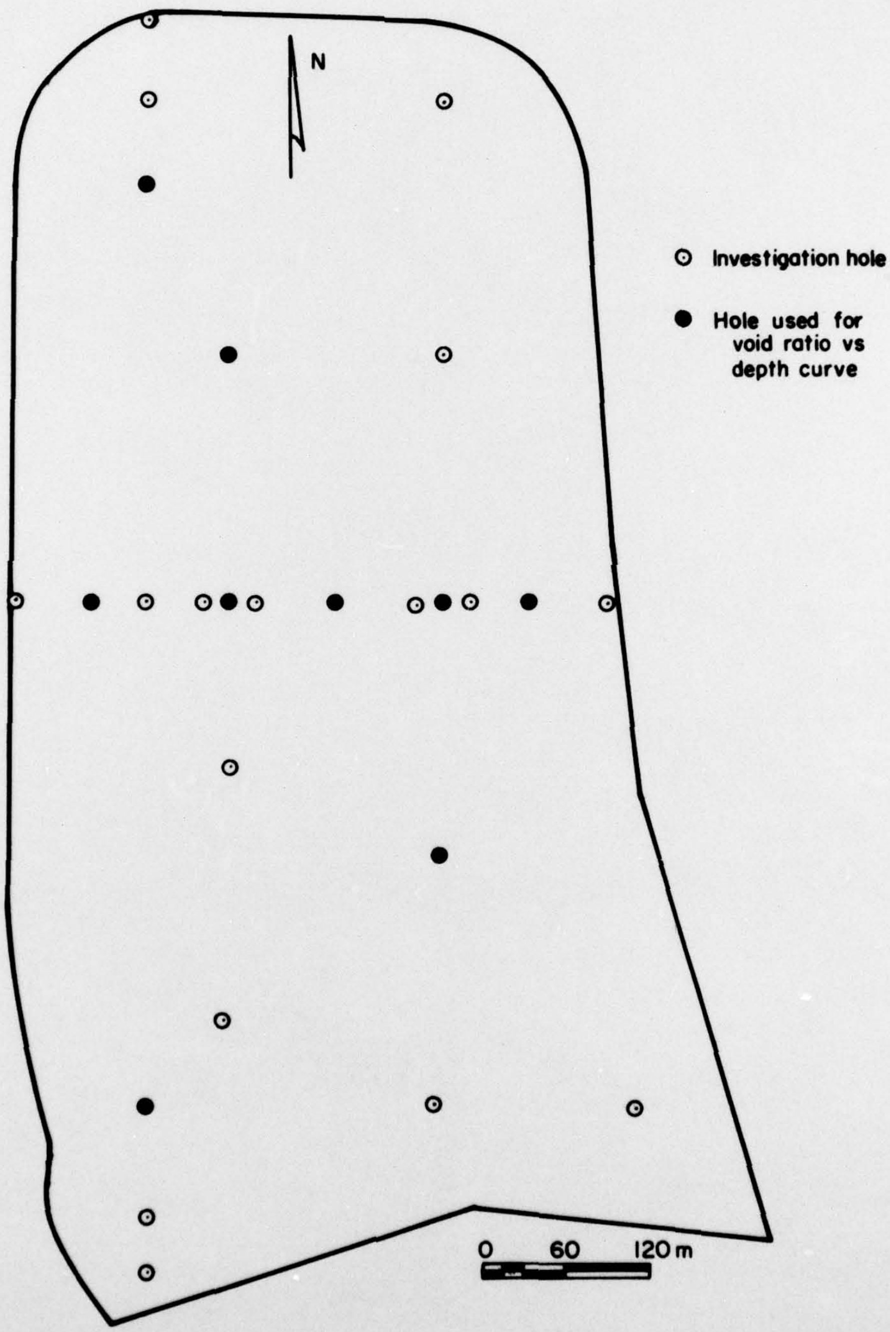

FIGURE A23. UPPER POLECAT BAY DISPOSAL SITE

APPENDIX B: NOTATION

C_c	-	compression index
CR	-	compression ratio
C_r	-	recompression index
CRSC	-	constant rate of strain consolidation test
c_v	-	coefficient of consolidation
dm	-	dredged material
e	-	void ratio
e_{ave}	-	average void ratio of dredged material
e_o	-	in situ void ratio of channel sediment
F_c	-	efficiency of containment system
F_e	-	efficiency of removal action
F_o	-	overdredging factor
F_p	-	efficiency of transport system
G_s	-	specific gravity of solids
H	-	height
H_i	-	thickness of layer i
H_2O	-	water
I_p	-	plasticity index
I_ℓ	-	liquidity index
n	-	number of layers
N.C.	-	normal y consolidated
RR	-	recompression ratio
S	-	degree of saturation
SGN	-	size and gradation number
t	-	time

t_{50}	-	time for 50% consolidation
t_{90}	-	time for 90% consolidation
u	-	pore pressure
$\bar{U}$	-	pore pressure dissipation
V_c	-	volume of solids retained in containment area
V_{CA}	-	required containment volume
V_{CAM}	-	measured containment volume
V_p	-	design volume of solids to be dredged
V_t	-	design volume of bottom sediment to be dredged
w	-	natural water content
w_l	-	liquid limit
w_p	-	plastic limit
Y_t	-	solids concentration (% by weight)
Z	-	constant
$-$	-	indicates an average value (ex. $\bar{e}_o$)
Δ	-	indicates a change
Δu	-	excess pore pressure
ρ	-	settlement
ρ_f	-	final settlement (100% consolidation)
ρ_{fdt}	-	settlement of foundation
γ_t	-	total unit weight
$\bar{\sigma}_v$	-	vertical effective stress
σ_v	-	total vertical stress
$\bar{\sigma}_{vf}$	-	final vertical effective stress
$\bar{\sigma}_{vm}$	-	maximum past pressure
$\bar{\sigma}_{vo}$	-	initial vertical effective stress

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Sizing of containment areas for dredged material / by Suzanne M. Lacasse, T. William Lambe, W. Allen Marr, Constructed Facilities Division, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, Mass. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1977.
157, 33, 2 p. : ill. ; 27 cm. (Technical report - U. S. Army Engineer Waterways Experiment Station ; D-77-21)
Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under Contract No. DACW39-75-C-0074 (DMRP Work Unit No. 4A16A)
References: p. 155-157.

1. Containment areas. 2. Disposal areas. 3. Dredged material. 4. Dredged material disposal. 5. Field investigations. 6. Sediment. 7. Size determination.

(Continued on next card)

Lacasse, Suzanne M
Sizing of containment areas for dredged material ... 1977. (Card 2)

I. Lambe, Thomas William, joint author. II. Marr, William Allen, joint author. III. Massachusetts Institute of Technology. Dept. of Civil Engineering. IV. United States. Army. Corps of Engineers. V. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Technical report ; D-77-21.
TA7.W34 no.D-77-21